PROTECTIVE RELAYS

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FIG. 1.—Typical switchboard of protective relays.

Frontispiece.

PROTECTIVE RELAYS

THEIR THEORY, DESIGN,
AND
PRACTICAL OPERATION

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PREFACE

In preparing a work of this nature, it will be realized that the subject is so broad and varied in its scope as to preclude an author's intimate personal knowledge of each and every system described. Attempt has been made to cover the subject from the first principles of Protective Relays to the protection of high tension net-works, the object being to make the work of value not only to the operator and tester who has a fair knowledge of electricity and is seeking more information, but also to the designer of the system who may find many points not previously taken into consideration in his calculations.

Consequently, many reliable sources of information were freely consulted and in several instances, passages were quoted verbatim from a booklet entitled "Performance of Instrument Transformers" and from "Protective Relays" which in turn was reprinted from an article by Mr. L. N. Crichton in *The Electric Journal*. Full credit is hereby given to the Westinghouse Electric & Manufacturing Company for such excerpts; also to the American Institute of Electrical Engineers for several paragraphs quoted from its June, 1919, *Proceedings*.

Some of this material has been published in the form of articles by the author in *Power, Power Plant Engineering, Electrical Record* and *Southern Engineer*, and thanks are hereby given to their editors for permission to use the text and electro-types for illustrations.

The author also wishes to extend his thanks and appreciation to Mr. F. A. Annett, Associate Editor of *Power*, for personal interest and assistance in the preparation of the work; to Mr. L. N. Crichton, Relay Engineer of the Westinghouse Electric & Manufacturing Company, and writer of several articles from which much valuable information was obtained, who kindly read this manuscript, and offered many helpful suggestions and constructive criticisms; and to officials of the Westinghouse Electric & Manufacturing Company, the General Electric Company and the Condit Electric Company, for valuable assistance in procuring photographs for illustrations.

<div align="right">Victor H. Todd.</div>

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PROTECTIVE RELAYS

CHAPTER I

WHAT ARE PROTECTIVE RELAYS

When the first electric generators were built and installed, no provision was made for disconnecting them automatically from the lines in case of trouble such as overload or short-circuits. This was overlooked for two reasons: (1) It was not considered detrimental to have service interrupted, as the electric system was more or less a novelty and in the experimental stage, and (2) the design of generators and prime movers was such that in case of heavy overload either the prime mover would stop, or the belt fly off, or the voltage drop so low that no electrical damage could be done.

However, as the mechanical and electrical design of generators and prime movers was gradually improved, it was noticed that in the event of a heavy overload, the increased current would burn out the weakest spot in the system; sometimes this was in the armature, sometimes in the wiring and sometimes in the switches. Naturally the result was to insert intentionally a weak spot at some convenient point in the system, by connecting a piece of wire much smaller than the main wires, so that when the overload occurred, this wire would burn out and then the operator knew just where to go and look for trouble when the power went off. This was the first fuse.

Installing the fine wiring near inflammable material led to another trouble; *i.e.*, fire risk, as during a heavy short-circuit, the wire was melted, and the red-hot metal thrown violently in all directions.

The remedy was to enclose the fuse in an insulating non-inflammable tube to prevent fires, and also to provide fuse blocks and clips so that the fuses could be replaced easily in case of an overload blowing them out.

Even today, there is no other piece of apparatus which can excel a properly designed fuse for reliability, and no matter what other protective apparatus is installed, as will be described later, there is hardly an installation which does not have fuses as an absolute guarantee of protection against heavy overloads, should the other protective apparatus fail.

Objections.—The greatest objection to fuses was the maintenance cost, or cost of replacement, as every time a fuse blew out, it meant a new fuse, and as the current capacity of the system went up, every new fuse meant considerable money. Not only that, but it took some time to locate atnd replace a fuse and besides, if a new fuse were not immediaely at hand, there, was a severe temptation to use a convenient piece of copper or solder-wire to complete the circuit, thus again introducing a a hazard. This improper replacement of fuses is one of the deepest-rooted evils in the electrical industry and is alone responsible for thousands upon thousands of dollars' worth of damage by fire every year, in addition to the burning out of many motors, generators and other apparatus.

In order to eliminate this replacement expense, as well as to restore service in a minimum of time, it was found necessary to develop an automatic switch which would open the circuit in the event of trouble. This was the forerunner of the present circuit breaker. There were many types developed and successfully used, but the principles and the objects accomplished were all the same; a coil carrying the main current was arranged to either attract an armature fastened to the switch blade and thus open the switch directly, or to attract an armature which in turn released a spring, thus allowing the spring to open the switch.

From the foregoing it would appear that the problem of protection was solved. But protection was not the only desirable feature; customers demanded continuous service and many times an interruption was caused only by a transient short-circuit; for instance, a wire or tool dropped across a switch, immediately falling off or burning out. It was not necessary for the breaker to open as the overload disappeared almost mimediately and if the breaker had not opened, service would have continued uninterrupted. In other words, the circuit

breaker had no discriminating, "reasoning" or "thinking" power. This led to the development of the protective relay.

Protective Relays.—The protective relay is an electrical instrument, generally accurate, sensitive, rugged and reliable in construction, interposed between the main circuit and the circuit breaker in such a manner that any abnormality in the circuit acts on the relay, which in turn, after the proper discrimination of the magnitude and characteristic of the abnormality, causes other apparatus such as a circuit breaker to function and relieve or protect the circuit and apparatus.

The great need of adequate protection and continuous service under all conditions has gradually caused the crude types of relays of a few years ago, which sometimes gave protection under special conditions but often failed at the critical moment, to be developed into present-day types, which are built with the accuracy of a watt-hour meter and can be depended upon in practically all conceivable cases of electrical distress.

In alternating-current systems, the need of continuity of service is so great that the lines must be kept alive until there is no chance of the disturbance clearing itself. In some states the public utility boards require an explanation of each and every interruption that occurs in an operating company's service as well as a report of the steps taken to prevent its recurrence.

Many power plants and factory managements have required in the past duplicate supply lines, so that their power supply would not be interrupted in case of trouble on other parts of the system. Others have maintained stand-by plants ready to assume the load in case of electrical trouble.

As a typical example of how protective relays have eliminated this necessity, one operating company had as many as 25 interruptions a year, but after making an intelligent survey of the system, a few changes were made in the sectionalizing apparatus and accurate relays installed which reduced the interruptions to about one annually, although the system suffered not less than 100 short-circuits per year from various causes.

The relays instantly sectionalize and isolate a defective line or piece of apparatus without disturbing the rest of the system. This allows spare lines to be used continually, and the

great saving and economy of copper will often finance the installation of relays.

Like a silent sentinel, the protective relay stands on guard on the lines, day and night, summer and winter, ready to detect trouble instantly, to determine if it is serious enough to open the circuit, and, if so, to disconnect faulty apparatus or sectionalize defective lines with almost human intelligence and more than human accuracy.

At present, the protective relays are so specialized and highly developed that there is practically no electrical defect or abnormal condition on a line that cannot be detected by a relay and the circuit protected against it. Excess current (generally called "overload"), under current, over-voltage, under-voltage, over and under-wattage, reverse current or power, high or low frequency, high or low temperature, reverse phases, and numerous other conditions which may occur. all can be detected by a suitable relay.

Principles of Operation.—As electricity is an intangible something which cannot be measured like water or gas, we must detect its presence and characteristics by the effect it produces The effects are four in number: chemical changes, heat, magnetism and static attraction. Although electrical-indicating instruments have been made to operate on all these various effects, yet practically all protective relays depend on the magnetic effect of an electric current for their operation.

The three main principles used are (1) the D'Arsonval principle, utilizing a moving coil reacting on a permanent magnet: (2) the solenoid and plunger type, utilizing the sucking effect of an energized solenoid on an iron plunger, and (3) the induction type, utilizing the same principle as employed in induction motors and watt-hour meters. Various relays operating on these principles will be considered in detail on following pages.

NOMENCLATURE

As relay development has been a gradual evolution, many firms developing a certain relay to overcome their particular troubles, it will be readily apparent why there should be such a wide variation in the nomenclature throughout the country.

In an effort to standardize and harmonize the nomenclature of protective relays the Protective Devices Committee of the A. I. E. E. recommended the following terms:

Protective Relay.—An intermediate electrical instrument by means of which one circuit is indirectly controlled by a change in conditions in the same or other circuits. The relay is generally equipped with contacts which are closed or opened mechanically by a change on one circuit and these contacts in turn close or open an auxiliary circuit electrically.

Directional Relay.—Any relay which functions in conformance with the direction of power, or voltage or current or phase rotation, etc.

Power-directional Relay.—Any relay which functions in conformance with direction of power. This includes both unidirectional relays with single contacts and duo-directional relays with double contacts. This term is to be preferred to "reverse power" or "reverse current" relays because this type is frequently used to function under normal direction of power. Furthermore, in some cases, the normal condition of the system may permit power to flow in either direction.

Polarity-directional Relay.—Any relay which functions by reason of change in polarity.

Phase-rotation Relay.—Any relay which functions by reason of a reversal of the normal direction of phase rotation.

Current Relay.—Any relay which functions at a predetermined value of the current. These may be either over-current relays or under-current relays and are commonly called "overload" and "underload" relays.

Voltage Relay.—Any relay which functions at a predetermined value of the voltage. These may be either over-voltage relays or under-voltage relays.

Watt Relay.—Any relay which functions at predetermined value of the watts. These may be either over-watt relays or under-watt relays.

Frequency Relay.—Any relay which functions at predetermined value of the frequency. These may be either over-frequency relays or under-frequency relays.

Temperature Relay.—Any relay which functions at a predetermined temperature in the apparatus protected.

Open-phase Relay.—Any relay which functions by reason of the opening of one phase of a polyphase circuit.

Differential Relay.—Any relay which functions by reason of the difference between two quantities such as current or voltage, etc. This term includes relays heretofore known as "ratio-balance relays," "biased" and "percentage-differential relays."

Locking Relay.—Any relay which renders some other relay or other device inoperative under predetermined values of current or voltage, etc.

Trip-free Relay.—Any relay which prevents holding in an electrically-operated device such as a circuit breaker while an abnormal condition exists on the circuit.

Auxiliary Relay.—Any relay which assists another relay in the performance of its function and which operates in response to the opening or closing of its operating circuit. Sometimes called "relay switches," "contactors" or "multicontact relays."

Signal Relay.—An auxiliary relay which operates an audible or a visible signal. Sometimes called "bell ringing relays."

QUALIFYING TERMS AS APPLIED TO RELAYS

Notching.—A qualifying term applied to any relay indicating that a number of separate impulses are required to complete operation.

Inverse Time.—A qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay decreases as the operating force increases.

Definite Time.—A qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay remains substantially constant regardless of the magnitude of the operating force. (For forces slightly above the minimum operating value the delay may be inverse).

Instantaneous.—A qualifying term applied to any relay indicating that no delayed action is purposely introduced.

Where relays operate in response to changes in more than one condition, all functions should be mentioned.

CHAPTER II

CIRCUIT BREAKERS AND RELEASES

In order to appreciate fully the action of the protective relays, it is first necessary to understand the action of circuit breakers, both how they may be equipped with certain releases which operate on abnormal conditions such as over and under current, etc., and also how they may be equipped with trip coils which are actuated electrically by protective relays.

As previously stated, the first circuit breakers were merely automatic switches, arranged with an electromagnet to cause the blades to fly open upon the occurrence of excess current in the electromagnet. Present-day circuit breakers break the circuit either in air or under oil. The first are commonly called "carbon circuit breakers" because the final break is between carbon contacts, and the second kind are often called "automatic oil switches," or "oil circuit breakers." Breakers may be semi-automatic, fully-automatic or electrically-operated. A semi-automatic circuit breaker is one which opens automatically on the occurrence of an abnormal condition, but must be closed by hand, and if the handle is held in a closed position, the breaker is inoperative. In the fully-automatic breaker, the handle is said to be "trip-free;" that is, if the breaker has opened due to an abnormal condition, and attempt is made to re-close the breaker by hand, then if the abnormal condition still exists, the breaker will open even though the handle be held in the closed position. An electrically-operated breaker is one which is both closed and opened electrically. The opening is usually due to an abnormal condition, but the breaker may be either opened or closed from some remote source, for instance a remote-control panel board or a protective relay.
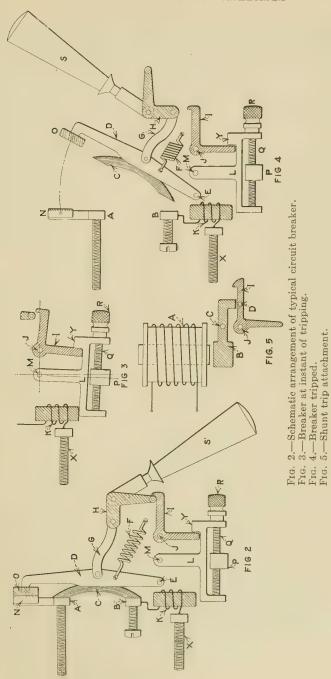
PRINCIPLE OF OPERATION

Circuit breakers are usually arranged so that when they are closed, considerable energy is stored in strong springs, and the parts held in a closed position by a small trigger or

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tripping lever. When the predetermined conditions occur for which the breaker is set, or when actuated by the protective relay, this trigger is tripped, thereby releasing the potential energy of the springs which causes the contacts to open in a small fraction of a second.

This may be seen readily from the schematic diagram of parts of a typical carbon circuit breaker as shown in Fig. 2, which shows the breaker in its normally closed position. A and B are the main contacts (usually heavy copper blocks), which are spanned by the laminated copper brush C. This is loosely attached to the moving arm D, in such a manner that it is self-aligning and when the breaker is being closed, contact C is forced against contacts A and B with great pressure, resulting in a "wiping" action which makes a good electrical connection. The moving arm D is pivoted at E and the springs F are under tension, tending to pull the contact open. This is prevented by the toggle joint G and H which is held in position by the trigger I (pivoted at J).

Connected between the lower stud on the breaker, and the lower main contact, is a coil K which carries the main current; and under its influence is an iron armature L pivoted at M. When the current in coil K becomes great enough, the armature L is attracted to its core; this causes a projection on the armature to strike the tripping lever a sharp blow, thereby releasing the toggle joint and allowing the springs to open the contacts quickly. In Fig. 3 is shown the breaker just at the instant of tripping and Fig. 4 shows the breaker fully open.

In order to reset, the handle S must be pulled down, thereby straightening the toggle joint, extending the springs and giving the necessary power to force the contacts into tight contact.

If the main contacts were to open the circuit directly, the resultant arcing would soon cause them to become so pitted that they could no longer make contact. Therefore, the circuit is finally broken by two auxiliary carbon contacts at N and O; when the main contacts open, the current is shunted through these contacts, but they are separated so quickly that no arc or excessive burning results, the oxide of course passing off as a gas.

Fig. 2.—Schematic arrangement of typical circuit breaker.
Fig. 3.—Breaker at instant of tripping.
Fig. 4.—Breaker tripped.
Fig. 5.—Shunt trip attachment.

In order to allow a variation in the tripping current required, the armature L is provided with a threaded weight P which is mounted on a worm Q and so its position may be varied by turning the nut R. When the weight is near the electromagnet K its full weight tends to keep the armature away from the electromagnet, thus requiring the maximum current to cause tripping; when it is near the nut R its weight tends to assist the attraction of K, thereby requiring a minimum of current.

Provision is usually made to open the breakers by hand. This breaker is opened by raising the handle S, which results in tripping. Many operators prefer to touch the trip lever I, or the nut R, to open the breaker, but this should be done with great caution as this part is "alive" and there may be danger of severe shock by touching. Many breakers provide for opening in this manner by using a well-insulated nut at R, thus preventing danger of accidental shock.

Shunt-trip Attachment.—It will be readily seen that anything which trips the lever I will cause the breaker to open. The shunt trip is a device for tripping the breaker, from some remote source, either manually or automatically by a protective relay. In Fig. 5 is shown the trip lever I pivoted at J, with the parts shown in Fig. 2 omitted for clarity. The electromagnet A is wound with many turns of fine insulated copper wire and is mounted on the side of the breaker as shown in Fig. 13. When this electromagnet is energized, it attracts the iron armature B, (pivoted at C) and this, striking a stud D on the tripping lever, causes the breaker to trip or open as before.

The shunt-trip attachment is the device usually employed when protective relays are used; upon the occurrence of conditions for which it is set, the relay closes the circuit to the shunt-trip attachment, thereby opening the breaker.

Underload Release.—There are cases, not important enough to warrant the use of an accurate relay, where a circuit must be protected from damage due to reverse current or under current. For instance if the charging source of a storage battery is interrupted, the battery may attempt to assume the load, or to motor the generator. However, the instant the current drops to zero (as it must do before reversing), the under-load attachment trips the breaker.

The principle of operation is shown in Fig. 6. The tripping lever is represented by J and I as before, and the device is shown ready to apply current. An electromagnet N (carrying the main current) is mounted on the side of the breaker as shown in Fig. 13. The heavy iron armature P pivoted at C has on its side a small lever D which is pivoted at E and is manually hooked over the stud F, thereby holding the armature a slight
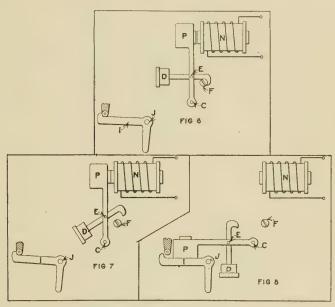
FIG. 6.—Underload attachment (normal position).
FIG. 7.—Underload attachment (ready to trip).
FIG. 8.—Underload attachment (tripped).

distance from the electromagnet N. When the electromagnet is energized, it attracts the armature P to the position shown in Fig. 7, thereby releasing the catchlever D.

Now should the current fail, the armature P is no longer attracted and from its own weight falls down to the position shown in Fig. 8, striking the trip lever a sharp blow and tripping the breaker. Care must be taken that the device "sets" itself when current is applied; that is, the iron weight must be attracted and the lever D released, otherwise the device will not operate on the cessation of current.

Under-voltage Release.—The foregoing device when wound with many turns of fine wire may be used as D.C. under-voltage release, operating when the voltage drops to a predetermined

FIG. 9.—Undervoltage release (normal position).
FIG. 10.—Undervoltage release (releasing).
FIG. 11.—Undervoltage release (released).

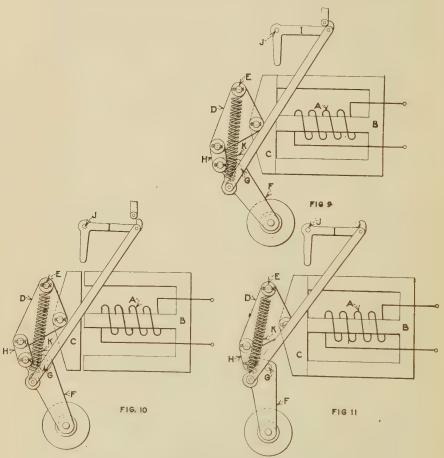amount. On alternating current, the electromagnet must have a closed-magnet circuit, and so the armature must be in the same position (closed air gap) in both operating and tripped position. This is accomplished by a toggle-joint arrangement

as shown in Fig. 9. I and J represent the trip lever as before. The coil A is wound on laminated iron core B which with the armature C forms a closed magnetic circuit. Attached to the back of the armature is a triangular piece D (pivoted at E) which is connected to the setting lever F (pivoted at G) by the link H which forms a toggle joint. The spring K tends to rotate F in a clockwise direction, and this, by attempting to straighten the toggle, would tend to give D a counterclockwise rotation and pull the armature away from the electromagnet. This is prevented by the energizing of A. As soon as the voltage drops to a predetermined amount, the armature is pulled away allowing the springs K to move the lever F, thereby tripping the lever I and causing the breaker to open. This position is shown in Fig. 10. But the springs pull the lever F further than the tripping position and this causes the link H and piece D to force the armature C back against the electromagnet, thereby again completing the magnetic circuit and preventing the coil A from burning out should the voltage come on again before the device reset. This is shown in Fig. 11. Resetting is accomplished simply by moving the knob to the position in Fig. 9. A breaker with this form of release is shown in Fig. 12.

Over-voltage Release.—For an over-voltage release a device somewhat similar to the shunt-trip attachment is used, but is usually designed with a heavier magnetic circuit to allow a smaller energy loss due to continuous operation. An over-voltage release is shown on the breaker in Fig. 14. The solenoid is wound on a heavy iron-casting and has in its center an iron plunger. When the voltage increases to a certain amount, the plunger is sucked upward, striking the pivoted lever which in turn strikes the projection on the trip lever and trips the breaker.

While practically every make of breaker varies in detail of construction, and in fact each manufacturer may turn out various designs of breakers, yet the principle of operation is practically the same in all and the foregoing examples are typical of the devices usually employed.

From the foregoing, it would appear as if the protective relay were a superfluous device, but it must be borne in mind that these releases are not at all accurate in their setting
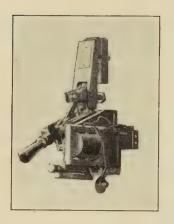
FIG. 12.—Undervoltage release mounted on breaker.
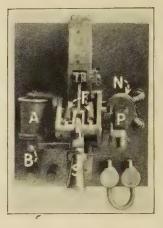
FIG. 13.—Breaker equipped with underload release and shunt trip attachment.
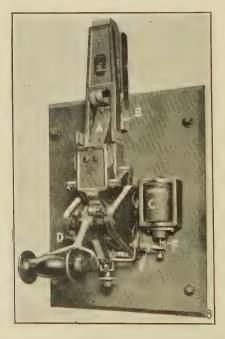
FIG. 14.—Breaker equipped with overvoltage release.

and may not always give adequate protection. On high-tension circuit it is often necessary to have the relays where they are easily accessible as, for instance, on the front of the switchboard, while the breakers may be in some remote and practically inaccessible location. Another point is that releases are often difficult to test and often more difficult to set to function on the desired predetermined conditions, and protective relays are becoming more and more to be recognized as a necessary adjunct to the well-equipped power plant and industrial concern.

CHAPTER III

TRIP CIRCUITS AND TIME DELAYS

Protective relays may be classified as circuit-closing and circuit-opening relays, according to the method employed to energize the trip coil of the circuit breaker. Circuit-closing relays are frequently called "shunt-trip" relays. It has already been shown how the circuit breaker may be opened by having an electromagnet which actuates the trigger when it is energized. The function of the protective relay is then, to complete the electric circuit which will energize this electromagnet or trip coil as it is usually called.

To accomplish this, the relay is equipped with two contacts; one stationary and one attached to the moving element. Normally these are not touching, but when the abnormality on the circuit reaches a certain predetermined magnitude, the moving element of the relay causes the contacts to touch each other or to close, thus completing the trip circuit and energizing the trip coil of the breaker, and causing the breaker to open.

Trip-circuit Sources.—It is evident that if the trip coil is wound for the proper voltage and frequency, it might be possible to operate the trip circuit from the same source as the protected source. But with no protection except a plain protective relay this will not be satisfactory, as in the event of a heavy short-circuit, the voltage may drop so low that there is not enough voltage to operate the trip coil, even though the relay should close the trip circuit; and it will be noticed that this low voltage occurs just at the instant when full voltage is most needed.

Even the practice of connecting the trip circuit to an exciter bus of the D.C. machines supplying the field of large alternators is not satisfactory, as a severe disturbance of the A.C. lines may be felt all the way back to the exciter buses, resulting in a failure of the tripping source at the most critical moment.

From this it is evident that the tripping-circuit source must be absolutely dependable and absolutely without connection to the

source being protected. The most dependable and suitable source for trip circuits is therefore a good reliable storage battery of about 100 to 125 v. It should constantly be borne in mind and also thoroughly impressed on the station operators that on this battery depends the success of the protective system and that the battery must always be in good condition and always in service as there is no telling at what instant a heavy "short" or overload will occur, and if the battery is taken out of service even for only a few minutes, yet it may be in that same interval that a "short" will occur and burn out much valuable apparatus. A diagram of connections for circuit-closing tripping is shown in Fig. 15.
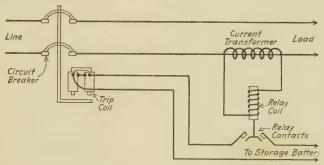

Fig. 15.—Elementary diagram of a circuit closing relay with separate trip circuit.

Auxiliary Relays or Relay Switches.—In view of the delicate operating or moving elements of protective relays, and their low energy consumption, it is evident that they cannot have large, bulky contacts, such as are necessary to close the heavy current necessary to energize the trip coils of the larger breakers. The average relay is designed with contacts to close (but never open, however) about 1 or 2 amp. at 110 or 220 v. When the breaker-trip coil takes more than this, or when it is necessary to operate several breakers upon the functioning of one relay, it is usual to have the protective relay close the circuit to an auxiliary relay (commonly called a relay switch, or a multi-contact relay), and this auxiliary relay in turn closes the circuit which energizes the trip coil of the breakers. The trip circuit should always be opened by auxiliary contacts on the circuit breaker and never by the relay contacts.

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Auxiliary relays, with their diagrams of connections, will be fully discussed in detail in another chapter.

Circuit-opening or Series Trip.—There are many installations of relays for plain overload protection in which it is considered too expensive to install and maintain a complete battery simply for tripping purposes. For such cases, the overload current itself is used as the energizing source, but the energizing of the trip coil is still controlled by the protective relay. In this system, the trip coil is put in series with the load; or in parallel with a shunt which is in series with the load; or connected directly to the secondary of a series transformer,
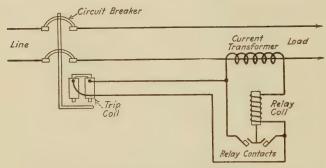

FIG. 16.—Elementary diagram of a circuit opening relay.

the primary of which carries the load current. But the protective-relay contacts are normally closed and are connected so that they short-circuit the trip coil, consequently the load current (or definite fraction of it) passes through the low-resistance contacts and very little flows through the trip coil. Now should an unusual disturbance occur, the contacts of the protective relay will open, and as the current can no longer pass through the contacts, it must flow through the trip coil, thereby energizing it and tripping the breaker. The diagrams in Fig. 16 show the connections for circuit opening or series tripping.

This method has a very serious drawback, however; if the contacts become slightly dirty, or make poor contacts due to vibration, they may shunt the current through the trip coil under normal conditions of load and trip the breaker without

cause. To obviate this defect, one company closes the contacts positively by means of a toggle joint, and this gives good protection and eliminates the danger of tripping out without cause.

Transfer Relay.—All of the advantages of the circuit-opening system have been regained and the former defects eliminated by the development of the so-called "transfer relay" which is shown in Fig. 17. While this relay is discussed at length in another chapter, yet it may be here stated that this system uses a circuit-closing relay as the protective device and when this relay functions, it short-circuits a "holding-down" coil on the transfer relay; this allows the transfer relay to function and in doing so it breaks the series circuit and instantly cuts the trip coil into this circuit, thereby tripping the breaker.

Time Delays.—Were it not for the fact that it is necessary to have a certain time delay between the instant of disturbance and the instant of breaker functioning, there would be but little field for the protective relay. There are three definite classes into which relays may be divided
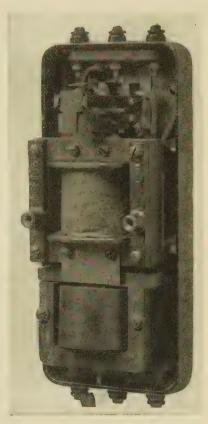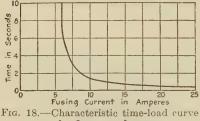

Fig. 17.—Westinghouse transfer relay.

according to time delay: instantaneous, inverse-time and definite-time.

As the name implies, the instantaneous relay provides no time delay between the instants of disturbance and tripping. Instantaneous relays are used generally where accurate protec-

tion is desired, and where there is almost no possibility of the disturbance clearing itself in a few seconds. For instance, if a transformer or a generator develops an internal short-circuit, there is practically no chance of it clearing itself and the

Fig. 18.—Characteristic time-load curve of a 6-ampere fuse.

transformer or generator should be cut out instantly. Or if a generator loses its field or if a battery which is supposed to be only charging, should suddenly start discharging due to the failure of the charging source, it is advisable for the circuit to be opened instantly, and for this purpose, the instantaneous protective relay is employed.

Inverse Time Limit.—This kind of time limit was the favorite for many years as it gave protection commensurate with the magnitude of the overload. By examining the time-delay curve of an ordinary fuse (Fig. 18) it will be
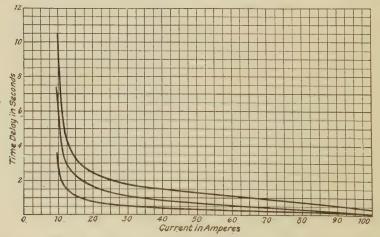

Fig. 19.—Characteristic time-load curves of G. E. inverse time limit, bellows type, overload relay.

seen that this inverse time protection is given, but of course on very heavy overloads the time becomes almost instantaneous. Figure 19 gives a typical curve of a plain inverse-time-limit

relay and readily shows how the time varies with the extent of the overload. For instance, consider curve *A*. This curve is taken with the relay set to close the contacts at 10 amp. at which setting it takes about 10 sec., this being on an indefinite part of the curve.

With the same setting and 20 amp. applied (*i.e* .200 per cent of load or 100 per cent overload) it takes only 2.5 sec.; at 50 amp. (*i.e.* 500 per cent of load or 400 per cent overload) it takes 1.3 sec.; at 100 amp. it takes only 0.4 sec., and above this the relay is practically instantaneous.

Definite-time Delays.—As the name implies, in this type of protective relay there is a definite time delay between the
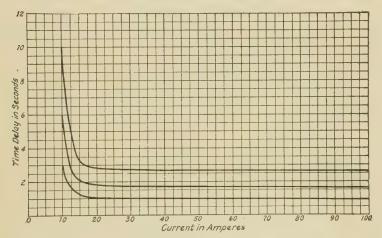
Fig. 20.—Characteristic time-load curves of a G. E. definite time limit, bellows type, overload relay.

instant of disturbance and the closing of contacts and this time delay is in no way affected by the magnitude of the abnormality. Such time delays have been successfully employed on a small scale, but have rapidly given way to the time delay described in the next paragraph. Typical definite time curves are shown in Fig. 20.

Inverse-definite-time Delays.—In this type of delay the latest practice is obtained by having the protective relay give a time delay which is inversely proportional to the magnitude of the overload up to about 1,000 per cent of load, but which

becomes a definite time limit upon any greater overload than this. For instance, consider the curve in Fig. 21, which is the time-delay curve of a modern induction-type overload
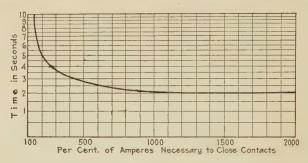
Fig. 21.—Typical time-load curve of a Westinghouse induction type overload relay.

protective relay. At 200 per cent of load the time delay is 5 sec.; at 300 per cent, 3.5 sec.; at 500 per cent, 2.5 sec.; and at 1,000 per cent and any overload above 1,000 per cent, the time delay is a definite 2 sec. Figure 22 shows another set of curves where definite time is approached at very heavy overloads.
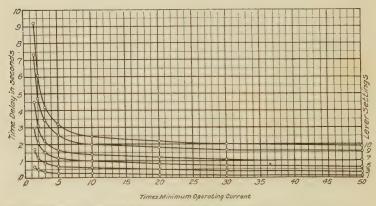

Fig. 22.—Typical time-load curves of a G. E. induction type overload relay.

The applications of these time delays, and how to set the various relays to obtain certain delays will be treated in detail in later chapters.

How Time Delays Are Obtained.—The method of lagging or damping the moving element of a protective relay depends largely on the principle of operation of the relay. In the direct-current type employing a moving coil and permanent or electro-magnet, the time delay is obtained by the use of an aluminum or copper bobbin which also serves as a support for the winding. It takes power to move the bobbin through the intense field and thus the movement, and consequently the time delay, is inversely proportional to the power applied, or in other words, to the overload.

In the solenoid and plunger type, some manufacturers employ a leather bellows with a small adjustable needle valve to allow the air to escape slowly. As the plunger attempts to rise, the air is compressed in the bellows, thus retarding the movement. Other manufacturers use a dashpot with oil to retard the motion.
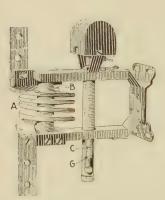
In the induction type, an aluminum disk rotates between strong permanent magnets which retard the motion. In this type, the definite time is obtained by having a small trans-former which saturates on heavy overload, thus limiting the power which is supplied to the relay windings.
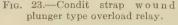
Other types use various novel methods which will be fully described under the various types of protective relays.

CHAPTER IV

PLUNGER-TYPE PROTECTIVE RELAYS

A relay operating on the effect of a solenoid to raise an iron plunger, thus closing or opening contacts, is shown in Fig. 23. Referring to the diagram of parts shown in Fig. 24, winding A is wound around the iron core B. Supported at the two poles N and S is an iron plunger C arranged so that it may slide up

Fig. 23.—Condit strap wound, plunger type overload relay.
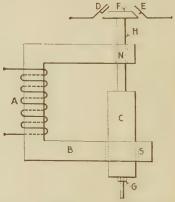
Fig. 24.—Schematic diagram of relay shown in Fig. 23.

and down. When the current in A reaches a certain value, the iron core C is lifted, thus closing the contacts D and E with bridge F, which will immediately trip the breaker, as previously described.

When the current is greater than 1,000 amp., a winding is not necessary, as the magnetism from the straight bar or cable produces sufficient flux to operate the relay. The relay may then take the form shown in Fig. 25, the cable simply passing through the large hole H, which is surrounded by insulating material. In Fig. 26 is another modification which may be used on a busbar that runs vertically instead of horizontally.

In this case the magnetic circuit is simply clamped around the busbar, which is of course insulated.
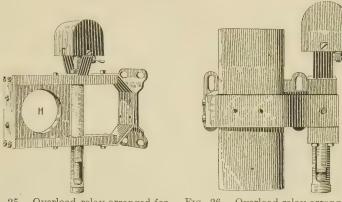
Fig. 25.—Overload relay arranged for horizontal bus.

Fig. 26.—Overload relay arranged for vertical bus.

Adjusting Relays.—In order to adjust these relays to operate on various loads, the plunger C, Fig. 23, is arranged with a nut
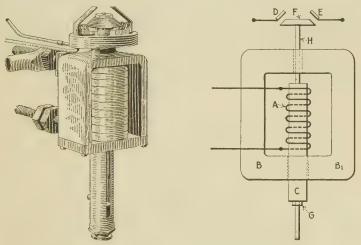
Fig. 27.—G. E. strap wound overload relay.

Fig. 28.—Schematic diagram of relay shown in Fig. 27.

G by means of which the plunger may be raised or lowered on the stem H. Thus if the plunger is at the lowest point, it will

take a maximum of current to raise it, but if it is set high, then it will rise on a minimum of current.

Another form of overload (excess-current) relay, utilizing the same principle of operation as those already described, is shown in Fig. 28. Coil A is wound on the central part over the iron plunger C, and the magnetic circuit is completed by the two parts B and B_1. The action is identical with the previously described relay; namely, when the current reaches a certain value, the plunger C is lifted upward, thus causing the contact
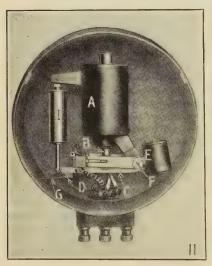
Fig. 29.

Fig. 30.

Fig. 29.—Interior view of obsolete Westinghouse definite time limit D. C. relay.

Fig. 30.—Shows the cover on and the time setting arm.

disk F to short-circuit the two contacts D and E, which complete the circuit that trips out the breaker. In another type of small capacity, adjustment is made by using taps on the winding; however, this cannot be done in capacities of several hundred amperes. The great advantage gained by the simple relay described further on has discouraged the use of plunger-type relays on direct-current circuits. If a plunger-type relay is to be used with a shunt, as has been done in rare cases, the adjustment for load is made by varying the drop of the shunt.

Figure 29 shows a definite-time relay with the cover removed and Fig. 31 gives a schematic diagram of parts. The solenoid *A* has an iron plunger *B* which under normal condition rests on the moving arm *C*, pivoted at *F*, which carries a contact *D* and a counterweight *E*. When the solenoid *A* is energized, the core *B* is raised upward instantly; relieved of this weight, the counterweight *E* now causes the contact *D* to start upward to meet the upper contact *G*. However, attached to the arm *C* is a piston *H* working within a cylinder *I*, which retards the movement of arm *C*, making it move very slowly as the air escapes around the plunger. Then, after a definite time, from 1 to 5 sec., depending on the initial distance between contacts *D* and *G*, the contacts *D* and *G* close, thus closing the circuit to the shunt-trip coil of the circuit breaker, causing the latter to open.
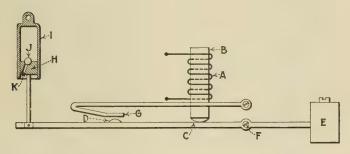
Fig. 31.—Schematic diagram of the definite time limit overload relay, Fig. 30.

If the current drops to normal before contacts *G* and *D*, Fig. 31, close, the solenoid allows the plunger *B* to drop, thus forcing the arm *C* downward into normal position. In order that the relay may reset quickly, a valve is provided in the dashpot plunger. This valve consists of a little steel ball *J*, which closes the air ports *K* when the piston moves upward and attempts to force air out of the port, but raises and allows the air to enter readily when the piston moves down as in resetting. Figure 30 is an outside view of a definite-time-limit relay similar to that in Fig. 29. This relay will close the circuit in the number of seconds that arm *A* points to on scale *S*. This relay is now practically obsolete, but there are still many in old installations.

The types of relays, Figs. 23 to 28, if desired, may close the circuit to a definite-time-limit relay instead of tripping the breaker instantly, but then, while the action is selective the cost renders its use prohibitive. Selective action, except in very heavy short-circuits, may be obtained by lagging the time of the tripping, and making the relay an inverse-time-limit device.
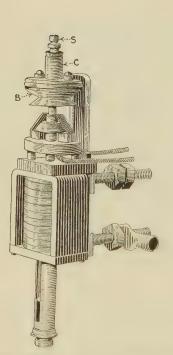
Fig. 32.—View of G. E. series type overload inverse-time-limit relay.

Fig. 33.—G. E. unit type bellows type overload relay.

That is, the greater the overload the quicker the time. In fact, in actual practice, the instantaneous relay has a very limited use; an inverse-time-limit relay costs only slightly more, gives the same protection and will not interrupt service on transient short-circuits. The latter type is shown in Figs. 32 and 33. The plunger, in rising, compresses the air in the leather bellows

B, which resists its upward movement.   In the top of the casting to which the bellows is attached, is an air passage *C*, which may be anywhere from 1 or 2 sec. to 20 or 30 sec.

The greatest objection to the bellows-type relay is that the leather, unless carefully attended to, will dry out and crack, making the permanence of time setting very unreliable.   To secure the best operation the bellows should be rubbed with neatsfoot oil every few months, and load-time curves taken. Otherwise the relays may fail at a critical time.   Another fault is that, while the time is inverse up to certain overloads, on short-circuits the time is almost instantaneous.   Therefore, if applied to a radial-feeder system, the action will be selective up to certain overload, but above this a breaker near the generator may go out as quickly as a breaker near the source of disturbance.   To overcome this difficulty, a plunger-type, overload, definite-time-limit relay was devised.

Time-limit Relays.—A definite-time-limit relay is shown diagrammatically in Fig. 34. The plunger *A* is not rigidly attached to the stem *B*, as in the type previously described, but slides freely on it.   If an overload occurs the plunger is raised and compresses the spring *C* which in turn forces the stem *B* upward against the resistance of the bellows *D* and finally closes the contacts *E* and *F* with the disk *G*.   It will be seen readily that no matter how severe the overload may be,
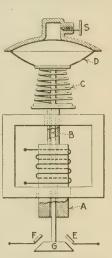
Fig. 34.—Schematic diagram of Westinghouse bellows type, circuit-closing, definite-time-limit, overload relay.

it can only compress the spring *C*; consequently, the upward pressure on the bellows stem is constant regardless of overload and the time is therefore constant.   The duration of time is varied by opening or closing the air valve *S* as described for inverse-time-limit types.   At the first glance this might appear the solution of radial protection, but it is impossible to depend on the relay for closer settings than 1 sec.; therefore, when there are four or five relays connected in a circuit, those near the generators must be set to operate in about 5 or 6 sec., which

is too long a time to sustain a dead short-circuit, especially near the generator. Then, too, the relays would trip just as quickly on a moderate overload as on a heavy overload, which is not at all desirable. Were the foregoing of great importance it would be necessary to perfect a relay accurate within small percentage of sustained accuracy and one whose curve was inverse up to certain overloads, after which it would become a definite-time-limit device. However, owing to the unquestioned superiority of alternating current for high-tension long-distance transmissions and the comparatively small size of most direct-current radial systems of transmission, relay engi-
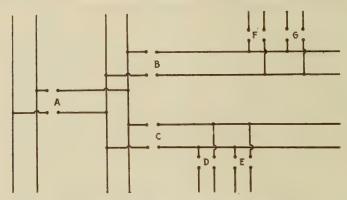
Fig. 35.—Elementary diagram of radial distribution system.

neers have devoted most of their energies to the perfection of alternating-current relays which are to a high degree perfect in their protection. In the large power plants or factories, however, where there are numerous machines that must be kept running unless actually damaged, a radial system of protection may be adopted with success.

This brings up an important use for definite-time-limit relays. Consider the distribution system shown in Fig. 35. Each time the line divides to supply a set of feeders, a definite-time-limit relay is supplied to operate a double-pole circuit-breaker. For instance, the feeder from the busbar is protected by breaker *A*, the next subdivisions are protected by breakers *B* and *C*, and the next by circuit breakers *D*, *E*, *F* and *G*. Suppose a heavy overload occurs on the feeder protected by breaker

D. The excess current extends all the way back to the main bus, and were definite-time relays not used, breaker *A* would go out as soon as breaker *D*, thus interrupting every circuit connected to the feeder protected by breaker *A*. But this is where the definite-time-limit relay enters in. The relay at *D* is set, say, for 1 sec., *B* and *C* for 2 sec., and *A* for 3 sec.
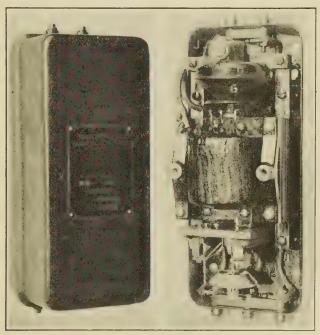
Fig. 36.—View of Westinghouse bellows type overload relay with and without protecting cover.

Thus when the disturbance occurs, all the relays of breakers *A*, *C* and *D* start to operate, but at the end of 1 sec., breaker *D* opens, relieving the excess current, and all the other relays reset quickly, confining the disturbance to the one line on which it occurred. Had the disturbance occurred on feeder *C*, then the breaker at *C* would have gone out in 2 sec.; breaker *A* would not have had time to open and feeder *B* would not have been interrupted. Figure 36 shows a typical overload relay which obtains the time limit by means of an air bellows, and Fig.

37 is a schematic diagram of the same. The iron plunger *A*, working under the influence of the solenoid *B*, carries at its lower end an insulated disk *D* having on its circumference a band of nonoxidizing metal. When the solenoid coil *B* is energized by a current of a certain strength, the core *A* is pulled upward, thus forcing the disk *D* against the contacts *E* and *F*, completing a circuit to a shunt-trip coil on a circuit breaker. On the upper end of the plunger shaft is a leather bellows *G* fastened to the permanent support *H*, so that as the plunger rises, it compresses the air in the bellows and resists its upward motion. This air is permitted to escape gradually through a little opening at *I* in the casting, and this gradual escape of air allows the plunger to rise in a certain time to complete contact at *E* and *F*.
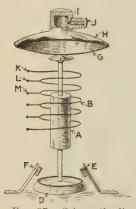
It is evident that the greater the current in the solenoid *B* the greater will be the upward pull, consequently the greater the compression in the bellows, the quicker the escape of air and the shorter the time. That is, the greater the overload the quicker the circuit will be opened.

This inverse proportion is not a fixed factor, however, since by varying the size of the escape aperture at *I* by means of the valve *J* the time may be varied from almost nothing to 15 or 20 sec., and still have the inverse time limit.

The taps *K*, *L*, *M*, etc., are provided to change the number of turns in circuit and consequently the amount of current required to operate the relay. For instance, this particular relay has taps for 4, 5, 6, 7 and 8 amp. This means that if the 4-amp. tap is in circuit, the plunger will start to rise when the current reaches 4 amp.; with the 5-amp. tap, the plunger will rise when the current reaches 5 amp., etc.

As a practical example, assume that the relay is used with a 100 to 5 current transformer. This means that when the full-load current of 100 amp. is reached there will be 5 amp.

passing through the relay coil. But if connections are made with the 4-amp. tap, the relay will operate on 4 amp., which, in the ratio of 5:100, means that it requires only 80 amp. to operate the relay with this setting. Should the 8-amp. tap be connected in, the relay will not operate until there is a load of 160 amp. on the primary of the transformer. This might take 18 sec. to trip the oil switch. But with the same setting, a load of 300 amp. might take only 4 sec.; 600 amp. 1.5 sec.; 1,000 amp. 1 sec.; and so on in time inversely proportional to the current.
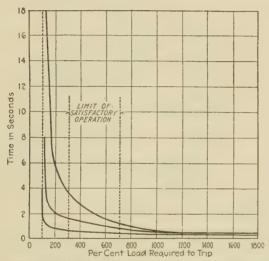
Fig. 38.—Characteristic time load curves of Westinghouse inverse time limit, bellows type overload relay.

This inverse time is not a straight-line inverse time, but follows a curve such as that shown in Fig. 38. It will be noticed that this curve is very similar to the time curve of a fuse, but has the distinct advantage that it may be varied at will, and the relay is accurate and can be depended upon, and is automatically reset each time it operates.

One relay is necessary for the protection of a single-phase circuit and two for a two-phase or a three-phase circuit, although three on three-phase give better protection. Figure 39 shows the diagram of connections of a single-phase circuit. *A* is the busbar supplying the feeder *B*, which in turn supplies the load

3

C, and the circuit breaker *D* opens and closes the circuit. *E* is the primary winding of a series transformer and *F* the secondary, which is connected to the relay and energizes the solenoid *H.* The direct-current circuit is connected to the shunt-trip
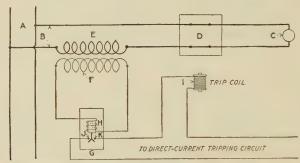
FIG. 39.—Elementary diagrams of circuit closing relay on single phase circuit
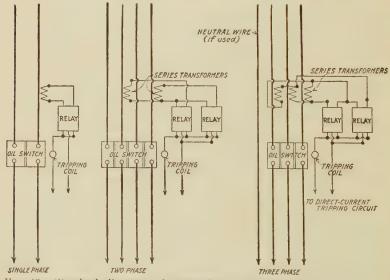
FIG. 40.—Standard diagrams of connections of Westinghouse bellows type, circuit closing, overload relays.

coil of breaker *D,* with a break in the circuit at contacts *J* and *K.* This diagram shows the normal operating position.

If an overload occurs at *C* and excess current in the transformer *EF* results, the relay plunger rises, short-circuits the

contacts *JK* and completes the trip circuit; an instant later
the oil switch will open, disconnecting the line.   Figure 40

Cover

Needle Valve Adjusting Nut

Lock Nut

Bellows Support

Tap for Quick Release Valve
When Used

Bellows

Compression Spring

Stationary Contact

Moving Contact

Contact Base

Plunger Stop

Frame

Magnet Frame Cover

Pole Piece

Plunger

Operating Coil

Magnet Frame Shell

Magnet Frame End Piece

Magnet Frame Supporting
Screw

Calibrating Rod

Calibrating Tube

Dust Cover

Adjusting Nut

Fig. 41.—G. E. unit plunger type relay.

gives diagrams of relay and transformer connections for pro-
tecting single-phase, two-phase and three-phase circuits.

Other Types.—Another bellows type of relay is shown in Fig. 41. This is a single-phase unit. Many relays were formerly made with two and three relays mounted on one casting to pro-
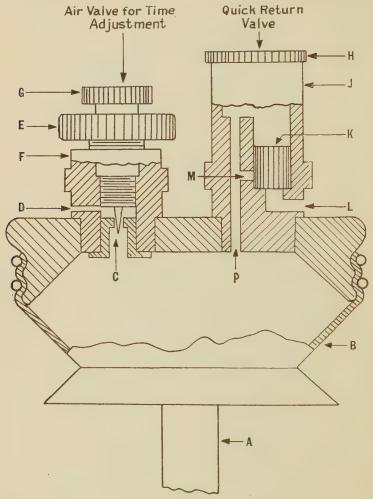
FIG. 42.—Air-valve and quick resetting valve on G. E. bellows type relay.

tect two- or three-phase circuits. These will still be found on older installations. However, they require two or three separate series transformers just as do the relays previously described.

It will be noted in this type that the contacts are at the top and protected by a removable cover, permitting ready inspection.

In this relay the various load settings are not obtained by taps, but by varying the position of the iron plunger in the solenoid by an adjustment at A. Lowering the plunger requires more current to raise it, and raising the position requires less current.
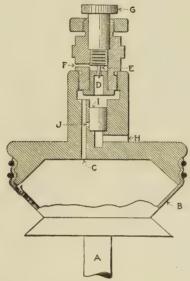
FIG. 43.—Early form of quick resetting air valves on bellows type relay.

The time setting is varied by an air valve in the top of the bellows casting, as shown in Fig. 42. When an overload occurs, the solenoid raises the plunger, thereby raising the stem A. This compresses air in the leather bellows B, forcing it up the channel C, and through the valve D. The time is adjusted by varying the position of the pin C by turning G. A good feature is the quick-resetting device shown at H and K. K is a cylinder which, on upward travel of the stem A, is forced against opening L and effectually closes opening M. When the relay attempts to reset, the air is rarefied in the bellows and cylinder K is lifted, allowing air to enter M and P, thereby insuring a quick resetting of the plunger.

An early form of quick resetting device is shown in Fig. 43, but one of the greatest drawbacks of this type is that on a heavy alternating-current overload, especially low frequency, the peak of the wave causes the air to compress in the bellows while when the A.C. wave passes through zero, this compressed air drives
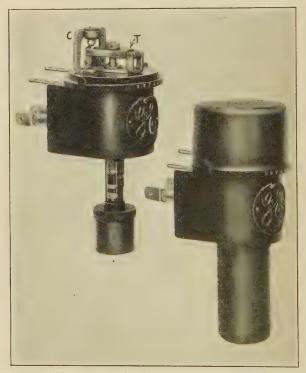
Fig. 44.   G. E. dashpot type, circuit-opening, inverse-time-limit relay, with and without protecting cover.

the plunger down a trifle and then the quick-resetting device admits air the wrong time. This recurring at every alternation drove the plunger so far down that it could not close the contacts.

One drawback to the leather-bellows-type relay is that the leather, unless attended to carefully, will harden in time and crack, thus defeating the purpose of an accurate time. To overcome this, relays of the type shown in Figs. 44 were

developed. These had the contacts at the top, as in the type Fig. 45, but the bellows is omitted and an oil dashpot was placed at the bottom of the stem as shown in Fig. 46.

Instead of forcing air through a needle valve, oil is forced by a piston on its upward travel through the valve E and out
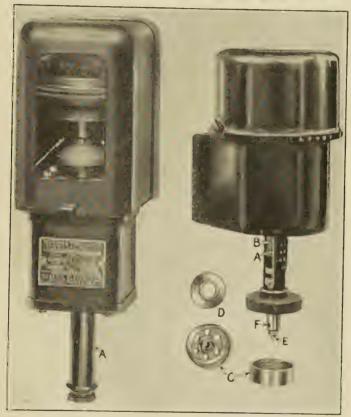
FIG. 45.   FIG. 46.

FIG. 45. (Left)—General Electric bellows type inverse-time-limit circuit-closing relay.

FIG. 46. (Right)—Shows details of the oil valve in the oil-damped relays.

of hole F, Fig. 46. The piston C has a number of holes in the bottom, which are normally covered by the disk D. Upon upward travel the disk closes the holes practically oiltight, but on downward travel it rises and allows a quick resetting of the plunger.

These relays cannot be used where they are subjected to extreme changes in temperature, and no other oil except that supplied by the manufacturers should be used in the dashpot. Their time may be varied from almost instantaneous at heavy loads, to over 5 min. at 150 per cent load.

Sometimes, as in radial systems, an inverse time is not so desirable as a definite time. To obtain this, the relays heretofore shown are slightly modified so that instead of the plunger being rigidly attached to the bellows and contact shaft, the raising of the plunger merely compresses a spring, which in turn
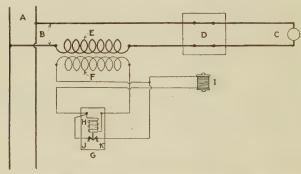
Fig. 47.—Elementary diagram of connections of series type circuit opening relay.

raises the shaft. This was shown in Fig. 34. The plunger A is free to slide up on the shaft B. When it rises, it compresses the spring C, which presses against a stop rigidly attached to the shaft, at the bottom of the bellows, thereby raising the shaft and contacts.

It will be readily seen that no matter how much current is passed through the solenoid, once it rises, there can be no greater compression from the spring no matter what the load. Consequently, the contacts are closed in a definite time, depending upon the time setting after the raising of the plunger. Hence the name, "definite-time-limit overload relay."

In the examples shown, it was assumed that there was always a separate direct-current circuit which the relay completed to trip the oil switch. Sometimes a source of direct current is not available, so the secondary current of the series trans-
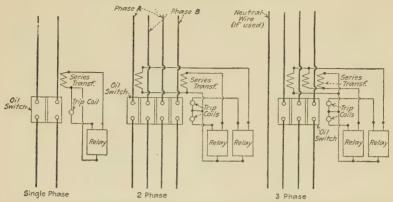
Fig. 48.—Standard diagrams of connections for Westinghouse bellows type overload circuit opening relays.
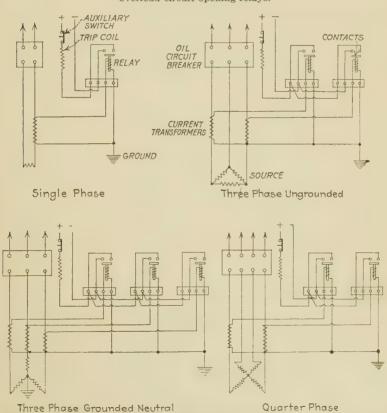
Fig. 49.—Standard diagrams of plunger type circuit closing overload relays as recommended by the General Electric Co.

former is used to trip the circuit breaker. These relays are
known as series-trip or circuit-opening types. The secondary
of the transformer is connected to the trip coil on the breaker,
but this coil is short-circuited normally by the relay contacts.
When the relay operates, it connects the trip coil in circuit,
thereby causing all the current to flow through it and open

Single Phase   Three Phase Ungrounded

Three Phase Grounded Neutral   Quarter Phase
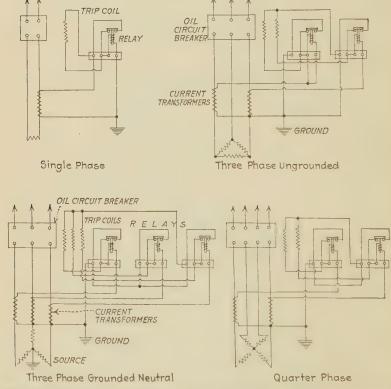
Fig. 50.—Diagrams corresponding to Fig. 49 except for circuit opening relays.

the oil switch. This is shown in Fig. 47, in which the feeder B
is supplying the load C through the current transformer's
primary E and protected by circuit breaker D. The secondary
of the transformer F is connected through the relay H and the
trip coil I on the oil switch D. The trip coil is short-circuited
by the contacts J and K on the relay. An overload at C causes

excessive current to flow in the relay coil H, which raises its plunger and opens the contacts J and K, causing current to flow through the trip coil I, which opens the oil switch.

One type of series-trip relay, Fig. 44, closes the contacts C by a toggle T, which is closed on the downward travel of the plunger, thereby insuring very positive connection. When the plunger rises, this opens the toggle, allowing a spring to open the contacts with a quick, positive action.

The series-trip relays have an advantage in that they do not require a separate circuit to trip the circuit breaker. However, unless they are equipped with solidly closed contacts, they are liable to trip the breaker on a slight jar or knock.

Figure 48 shows the standard diagrams of connections furnished by the Westinghouse Co. for circuit opening relays, corresponding to the circuit closing diagrams shown in Fig. 40. The General Electric Co. furnish the diagrams shown in Fig. 49 for one, two and three phase protection by circuit closing relays. The corresponding diagrams for circuit opening relays are shown in Fig. 50.

CHAPTER V

D.C. POWER-DIRECTIONAL RELAYS

During the early days of the electrical industry the problem of the protection of circuits and equipment was one in which the chief concern was given to disconnecting the fault as quickly as possible. This generally could be accomplished by the use of fuses or circuit breakers with an instantaneous trip. However, as the size of electric-power systems increased and they were complicated with a multiplicity of circuits and apparatus, and the necessity of continuity of service became an important matter, the problem of protection developed not only into one of protecting the apparatus, but also of localizing the fault to the circuit on the piece of apparatus where it occurred. To meet the various conditions of protection required for machines operating in parallel, or in parallel with other equipment, or for isolating the faulty circuit in the various feeder systems, there have been developed a number of different types of relays. Among these devices the reverse-current relay has, especially in the protecting of direct-current circuits and apparatus, a wide application.

One of the prime applications of the D.C. power-directional relay is for the prevention of the reversal and the discharge of current from a storage battery into the charging source should the voltage of the charging equipment fail. In addition to this there are numerous other applications where the power-directional relays may be used. Rotary converters operating in parallel with a stand-by storage battery is another case in which a highly sensitive relay of the reverse-current type is required. Or where rotary converters are operated in parallel, if the alternating-current supply fails on one machine it will be motorized from the direct-current bus. Even if the alternating-current supply is interrupted only for a short time, it is unsafe to run the converter inverted although the power consumed is very small, since it may run at damaging speed,

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and in any case, were the alternating-current supply to be established after a very short interruption, the converter would not be running in synchronism and might cause considerable damage. Therefore the power directional relay must be highly sensitive and trip the breaker immediately upon a slight reversal of power in the direct-current end.

Figure 51 shows a D.C. power-directional (reverse-current) relay with the cover removed, and Fig. 52 is a diagrammatic scheme of connections.

In Fig. 52, A is the magnet frame and B an iron core about which the moving coil C is free to turn on jeweled bearings at the top and bottom of the coil, very similar to the permanent-magnet movement voltmeter or ammeter. The field coil D is wound with a large number of turns of fine wire connected directly across the circuit and magnetizes the polepieces N and S. It will be noticed that the potential on coil D does not reverse, no matter which way the current is flowing in the circuit; consequently, the polarity of the magnet is always the same. The movable coil is connected through spiral springs, the same as a movable coil in a direct-current ammeter or voltmeter, to the shunt, which is in series with the load. When the current flows in the proper direction, the turning effort, or torque, of the movable coil tends to keep the contact E firmly against the stop F and is also held in this position by the spiral springs. But if the current reverses in the circuit, the current through the movable coil is reversed, consequently the torque, therefore contact F moves over against G. This closes a circuit to the shunt trip on the circuit-breaker and opens the circuit. Or if desired, it may close a definite time-limit relay, which in turn closes the trip circuit. The position of the stop F and the contact G is variable, so that the contacts will not close until the load has reversed to a definite predetermined amount. This relay has a scale marked in millivolts as shown in Fig. 51, and may be set to act as low as 2 per cent reversal of current or as high as 100 per cent.

The closing torque of this relay is proportional to the load, owing to the restraining effort of the spiral springs, consequently can be used as an excess-current relay since its time is inversely proportional to the excess current. Thus if the disturbance is
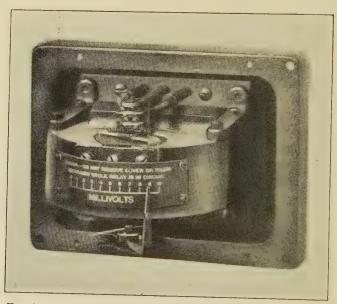
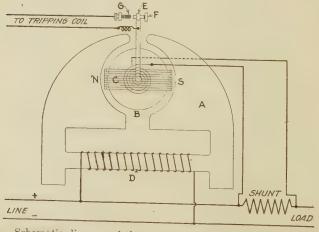Fig. 51.—Movable-coil type reverse-current relay (Westinghouse).

Fig. 52.—Schematic diagram of the movable-coil type relay shown in Fig. 51.

mild, it may take as high as 8 sec. to close, allowing ample time for
a transient disturbance to clear itself.   If the disturbance is more
severe, it may take only 1, 2 or 4 sec., depending on the violence of
the disturbance, while on a dead short-circuit the action in closing
the contacts is almost instantaneous.

Figure 53 shows another type of D.C. power-directional
relay, which is not, however, capable of such accurate pro-
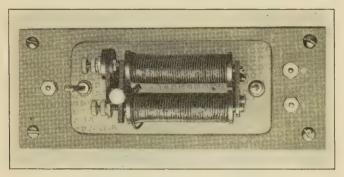
Fig. 53.—Polarized reverse-current relay (Westinghouse).
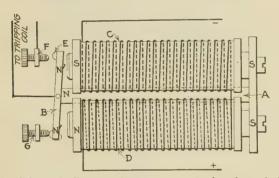
Fig. 54.—Schematic diagram of reverse current relay shown in Fig. 53.

tection. A schematic diagram of this relay is given in Fig.
54. A is a permanent bar magnet, with poles N and S. Pivoted
on the end of the magnet is an iron armature B which has its
ends polarized N' and N' by magnetic induction. The iron
cores of coils C and D also serve to complete the magnetic
circuit of the bar magnet. The coils are wound to produce
poles N and S at the armature end with the current flowing

in a normal direction. Then the N end of the lower coil repels the armature N' and the S end of the upper coil attracts the armature. This keeps the contacts E and F open. Should the current reverse, the polarity of the electromagnets is reversed and the armature end of the lower coil will become S polarity, which will attract the armature N', while the upper coil will become N and will repel the armature N'; therefore the armature moves over and closes the contacts E and F on
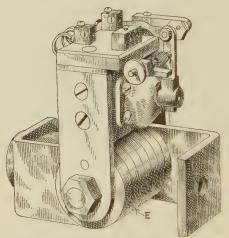
Fig. 55.—G. E. strap-wound reverse-current relay.

reversal of the current, which in turn may close the circuit to a relay switch, definite-time-limit relay or the shunt-trip coil on the circuit breaker.

The relay may be adjusted to operate on a definite reversal by changing the position of the stop G or by varying the millivolts drop across the relay-coil leads. The millivolts drop may be obtained by connecting across a length of copper busbar. Allowing 1,000 amp. per square inch of cross-section, 6-ft. length of busbar will give 50 m.v. drop. A correspondingly heavier current per square inch will give the drop with a shorter span. Care must be taken that the relay leads span only the solid copper—that is, there is no joint included as a slight resistance of a joint may equal several feet of busbar and the

resistance of joint is generally unstable. The drop obtained in this manner will vary greatly with the heat, as the resistance of copper increases with a rise in temperature. This, however, should cause no trouble, as power-directional relays of this type should never be set or reliance placed on a setting when a variation of 5 to 10 per cent might mean the difference between correct and incorrect operation.

In Fig. 55 is shown a type of power-directional relay that has its current and potential coil reversed from that in Fig.
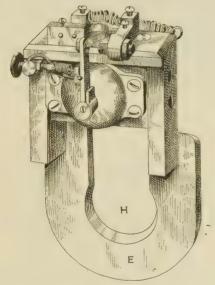
Fɪɢ. 56.—Relay arranged for horizontal bus.

51. The exciting coil *E* is wound with heavy copper strap, and the potential coil located in the upper part of the relay is wound with fine wire placed in series with a resistance and connected across the circuit.

In the relay shown in Fig. 56 the current coil is dispensed with, as the iron yoke *E* forms the winding and gives enough magnetism for operation simply by passing the circuit-breaker stud or terminal, where the relay is mounted, through the hole *H*. Figure 57 shows a similar type, but is arranged for mounting on a busbar. The reverse-current relay, Fig. 58, operates

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on a somewhat different principle from those in Figs. 55, 56 and 57. This is shown diagrammatically in Fig. 59. The iron magnetic circuit *A* has a gap *B* on one side and an iron yoke
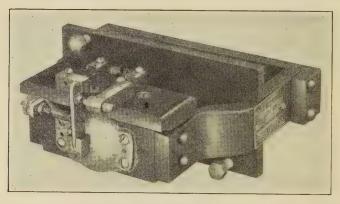
Fig. 57.—Reverse-current relay arranged (G. E.) for bus-bar mounting.
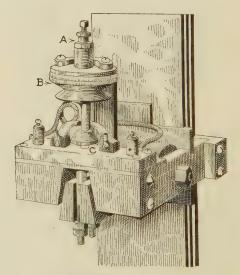
Fig. 58.—Relay for vertical bus.

C across its center. If the current in the heavy busbar *D* is flowing in the direction of the arrow, it will magnetize the yoke with a polarity as shown. The winding *E* is wound with

a large number of turns of fine wire and is connected across
the circuit so as to produce a polarity in core C, as indicated. It
is evident that the effect of the current in the busbar and that
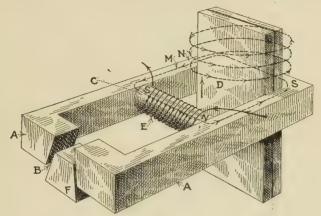
FIG. 59.—Schematic diagram of reverse-current relay.
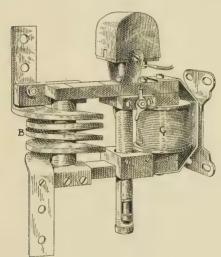
FIG. 60.—Condit strap-wound reverse-current relay.

in coil E is such as to cause a flow of flux through the mag-
netic circuit formed by the magnet A and the yoke C of the
potential coil E, as indicated by the dotted line M. Very little

magnetism will flow through the part of the magnetic circuit containing the air gap B. Should the current reverse in the busbar, however, the magnetism will also reverse and oppose that of coil E, but they will both unite in forcing the magnetism through the part of the circuit containing the air gap B. In air gap B is an iron core F, and when the magnetism becomes great enough, the core will be atracted upward, thus

Fig. 61.   Fig. 62.
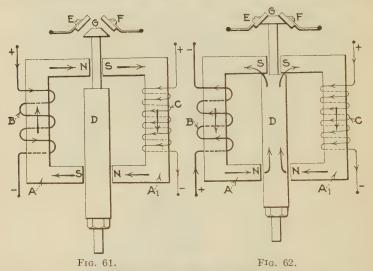
Fig. 61.—Diagram showing polarity with current in normal direction.
Fig. 62.—Diagram showing polarity upon current reversal and closing of contacts.

closing the contacts C, which are shown clearly in Fig. 58. This type of relay is given an inverse-time characteristic by equipping it with a retarding bellows B, which may be adjusted by the air valve A on top of the relay.

Another slightly different form of power-directional relay is shown in Fig. 60. An iron plunger is used and two coils are placed on opposite legs of the iron magnetic circuit. The arrangement is shown diagrammatically in Fig. 61. The iron magnetic circuit A and A', has a current coil B on one leg and a potential coil C on the other leg, with a core D located between A and A', arranged to move vertically. With the current flowing in normal direction the magnetism travels up one leg

and down the other, as indicated hy the arrows. There is no magnetism or at least a very weak field in the core D under normal load. Should the current reverse in B, then both
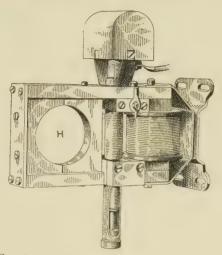
Fig. 63.—Relay arranged for horizontal bus.
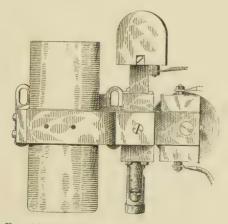
Fig. 64.—Relay arranged for vertical bus.

coils tend to force the flux through the core D. When this reversal is sufficient to force enough magnetism through the core, it is lifted up and closes the contacts E and F by the

contact disk G, as in Fig. 62, which in turn closes the circuit to a breaker-trip coil.

When the current is 1,000 amp. or more, the current coil is omitted and a relay like Fig. 63 is used, the cable or bus passing through the insulated hole H, the magnetic field set up about the cable being sufficient to operate the relay. If the relay is to be used with a vertical busbar instead of a horizontal one, the parts are slightly rearranged as shown in Fig. 64, but the principle of operation is the same.

There are other relays utilizing similar principles of operation, but before selecting any relay for a particular service, the characteristics of the relay should be carefully studied as well as the character of the installation to be protected, and a relay chosen which gives a maximum of favorable points. Applications of D.C. power-directional relays will be fully discussed in the next chapter.

CHAPTER VI

APPLICATIONS OF D.C. POWER-DIRECTIONAL RELAYS

There are numerous cases in which power-directional relays may be applied not only to give complete protection to D.C. apparatus but also to preserve continuity of service in case of failure of lines or machines. While their general use has been limited by the initial cost and the relatively small sizes of D.C. transmission systems compared to A.C. systems, yet they are becoming more and more to be recognized as an indispensable factor in the correct operation of any plant. Another reason why they have not come into general use in the various plants is because the users of electric energy have grown into the habit of considering an interruption as a part of their everyday work; an unavoidable evil. Were the protective relays better understood, it would at once be realized that interruptions are not a *necessary* evil, but a large percentage of the interruptions on many systems may be avoided by the proper use of protective relays.

Storage-battery Protection.—The primary application of a D.C. power-directional or reverse-current relay is to protect a charging storage battery from discharging should the charging source fail. If the battery is being charged by a small motor generator, a failure of the motor may cause the battery to motorize the generator, thus exhausting itself. Even if the battery is being charged from a line circuit through a resistance, a failure of the line will cause the battery to discharge into the line through the resistor. If being charged by a mechanical rectifier, a failure of the alternating-current may cause the battery to discharge through the rectifier coils. However with a mercury-arc rectifier or a vacuum-tube rectifier such as the "Tungar" or the "Rectigon" the battery cannot discharge in case of A.C. failure.

Figure 65 shows a diagram of connections giving the direction of current in battery, generator and load. Figure 66
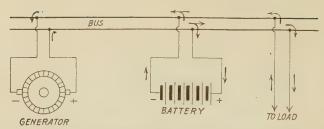
Fig. 65.—Diagram of connections of battery, load and generator. Arrows show normal direction of current flow.
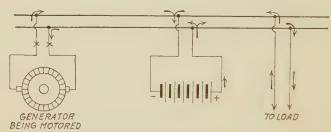
Fig. 66.—Arrows show direction of current flow upon failure of generator.
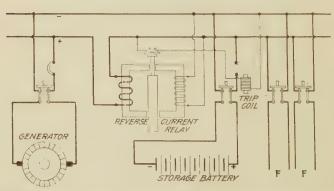
Fig. 67.—Diagram of connections for battery, load and generator for protection against current reversal.

shows the direction of current upon the failure of the generator.
It will readily be seen that the battery attempts to assume the
load and shows the correct location for the application of a
reverse-current power directional relay.
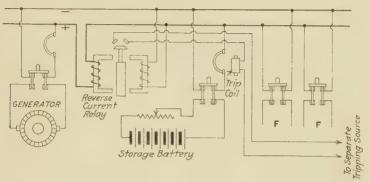
Fig. 68.—Connection diagram of relay using separate tripping source.

When the battery is of sufficient voltage, the trip circuit
may be taken directly from the battery, but if the battery
is of low voltage, the trip must be taken from another source.
Figures 67 and 68 show diagrams of connections of a simple
relay protecting a battery against reversal of current.

Other Methods of Protection.— For the average small installa-
tion, the expense of a good relay is prohibitive and other methods
will give adequate protection. If the voltage of the battery
is very low, then a no-voltage release may be connected to
trip the breaker or sound an alarm. But it must be borne
in mind that if the voltage of the battery is sufficiently high
then if the charging source should fail, the battery will still
maintain a line voltage and will prevent the functioning of
the no-voltage attachment, thus defeating the purpose for which
it was installed.

Even should the battery be charged by a motor generator,
or rotary converter, a no-voltage device on the A.C. side must
be used with great caution, as the battery may motor the genera-
tor and generate sufficient A.C. voltage to prevent the function-
ing of the A.C. no-voltage device.

Other methods utilizing the no-load and the reverse-current releases have been fully described under the chapter on "Circuit Breakers and Releases."

POWER-DIRECTIONAL RELAYS AND STAND-BY BATTERIES

When the battery is large enough and is designed to carry part or carry all the load in the event of charging-source failure, as for instance in the case of a rotary converter charging the large stand-by battery of an elevator or mine-hoist system, it is evident that the battery must not be disconnected in case of current reversal.
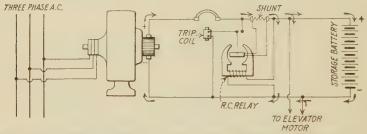
Fig. 69.—Connections of rotary converter, storage battery and elevator motor. Arrows show normal direction of D.C. current.

In order to determine the correct point of application for the relays, let us consider Fig. 69, which shows a rotary converter, feeding a stand-by battery and the elevator-motor load.
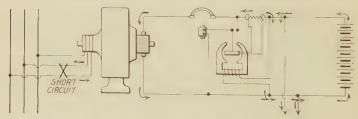
Fig. 70.—Arrows show direction of current with a short circuit on the A.C. line.

Now should the A.C. power fail, due for instance to a short in the A.C. line as shown in Fig. 70, at *X*, then the battery will attempt to feed the rotary (D.C. end), run it inverted, generate alternating current and feed through the short at *X*. Or even if the A.C. supply is only interrupted for a short time, it would

be unsafe to run the converter inverted although the power
it consumes is very small; for it may run at damaging speed.
In any case, were the alternating current to come on suddenly,
it would not be running in synchronism, and might cause
considerable damage. Therefore, the reverse-current relay
must be installed between the rotary-converter and the load.
It must be very sensitive and trip the breaker immediately
upon a slight reversal of power in the D.C. end. The rotary
must then be restarted, and resynchronized (if not of the self-
synchronizing type) and the voltage readjusted before recon-
nection to the D.C. system. This case calls for the highest
grade of relay as it must be set to trip the breakers instantly
on a reversal of current of only 1 or 2 per cent of normal load
current.

If the battery is not large enough to carry the full load, then
a reverse-current power-directional relay may be installed
in the battery circuit to limit the discharging load by tripping
several of the unimportant circuits. In this case, however,
much better operation is assured by using the relay not to
trip the circuits directly, but to sound an alarm, thus warning
the operator to pull feeders until the safe load of the battery
is reached at which point the alarm will cease.
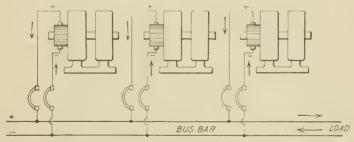
Fig. 71.—Arrows show direction of current with three generators feeding bus.

Failure of Prime Movers.—A similar case is where the gen-
erators may be run from water or steam turbines, or other
type of engine, where they may be connected in parallel, feed-
ing the same bus, or charging a stand-by battery. Consider
Fig. 71, showing three generators, each with its separate prime
mover, tied into one bus. Each generator should be supply-

ing its own share of the load. But suppose the prime moving source of generator No. 2 should fail. Being connected to a live bus, the current would reverse, it would run as a motor, and keep the prime mover running as a load instead of a mover, the currents being as shown in Fig. 72.

FAILURE *(Now being motored)*
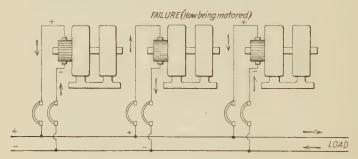
Fig. 72.—Arrows show direction of current flow upon failure of one generator.

Suppose the failure should not be due to the prime mover, but due to generator No. 2 losing its field (accidentally disconnected from exciting circuit). There would still be a weak residual field upon which the heavy reverse current might react, run the motor and prime mover at terrific speed, breaking the flywheel or doing other material damage. Still the current might be less than full-load current.

A reverse-current relay inserted between the generator and protecting breaker would prevent this. On the least reversal of current, the relays would quickly close its contacts, tripping the breaker, which could not be closed until the conditions were correct for normal operation. This scheme should not be depended on alone to disconnect a generator with lost field, as every important machine should be equipped with a centrifugal device which instantly opens the circuit in the event of excess speed.

Parallel Feeders.—Heavy D.C. installations sometimes tie in a sub bus with several tie lines, some of which formerly were used as spare lines to be used only in case of emergency. Sometimes important machines have their motors fed by several feeders. By properly connecting in reverse power relays with overload-and-definite-time-limit relays, every feeder may

be used, with a great economy in copper, and a faulty feeder disconnected immediately without interruption of service, allowing the other cables to carry the load at overload until the damaged line can be repaired. Figure 73 shows the main bus tied into a sub bus by two feeders and protected at the gen-
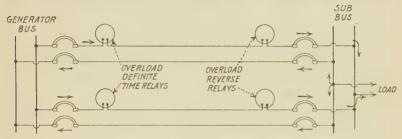
Fig. 73.—Normal direction of current in parallel feeders.

erator end by overload-and-definite-time-limit relays, and at the sub end by reverse-current relays. If a heavy excess current occurs on the sub bus, relays *OD* and *OD′* will trip the breaker on each feeder at the generating end. But a short on a bus inside the station is of a very rare occurrence. Suppose, however, a short occurred on the feeder at *X*, Fig. 74. This
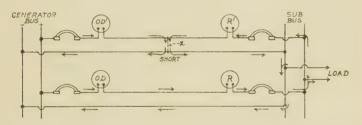
Fig. 74.—Arrows show direction of current with a short circuit on one feeder.

short will be fed from both the generating end and the sub end, thereby putting a heavy load or excess current on each feeder. Both relays start to act at *OD* and *OD′*, but the current in relay *R′* has reversed, so before either *OD* or *OD′* can trip their breakers, *R′* trips its breakers, thus relieving the excess current on the first feeder. The excess current is not relieved from relays *OD′*, however, so in a second or so they trip their breaker,

effectually cutting the bad feeder from service at both ends and still allowing the first feeder to feed the bus load without interruption.

When there are a number of feeders in parallel, they may be equipped with plain overload (excess-current) relays with an inverse-time-limit. Due to the current in the faulty feeder being greater than in the other feeders, the inverse-time delays will usually enable the relays to discriminate and trip out the faulty feeders. This condition is practically the same on D.C. and A.C. and is discussed in detail under the chapter on the "Protection of Parallel Feeders by Excess-Current Relays."

D.C. Ring Systems.—Sometimes there is an apparatus which must be run without interruption except in case of actual damage to the apparatus itself, and even then the interruption must be confined to the smallest possible area. To this end, spare feeders or lines are often run to each piece of apparatus, and in case of trouble on one line, the other is switched on.

If the apparatus is connected in a ring system, and power-directional and definite-time-limit relays supplied, the faulty feeder or piece of apparatus may be automatically cut out without interruption to the rest of the system. As shown in Fig. 75, the tie lines between the motors are all equipped with relays which trip only when the power flows *away* from the apparatus. Then the relays on the side away from the main bus as at A, B, C, D and E are set for a decreasing time element, as for instance A for 5 sec., B for 4 sec., C for 3 sec., and so forth. The other relays, going around the other way, F, G, H, I and J are also set with decreasing time element, as F for 5 sec., G for 4 sec., and so on. The feeders are protected at the bus by overload-and-definite-time relays having a time element slightly longer than the longest reverse-current relay.

Now, remembering that a relay will only trip when the current flows *away* from the sub buses, and never when it flows into them, consider the effect of a short circuit at X, Fig. 76.

An excess current will flow in the direction shown and relays A, B, C and D will start operating; also F and the main relays K' and K. But D has the lowest setting of any of the ones that start operating. So at the end of 2 sec., relay D trips its breaker, thus relieving the excess current on A, B, C and K, which imme-
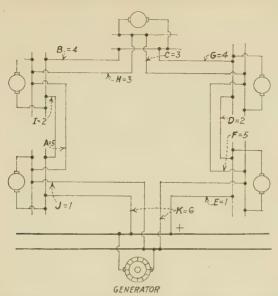
FIG. 75.—Elementary two-wire ring system for feeding motors an uninterrupted supply.
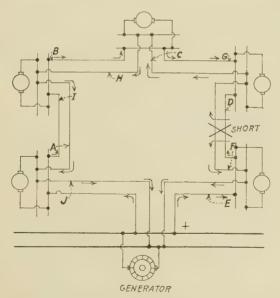

FIG. 76.—Arrows show direction of current flow with a short circuit between stations.

diately reset. The excess current is still actuating relays F and K, but as F is quicker than K, F trips its breaker before K, thus relieving the excess current and K resets.

Thus it will be seen that the faulty line is disconnected at both ends and every motor is still running without interruption. A disturbance at any point of the whole system will thus clear itself. Even if the motor were defective, the lines supplying it would be automatically opened on each end and would cut out only the defective unit and allow the others to run without interruption.

To expand this system of protection, large industrial plants may be substituted for the motors and be fed in a ring without interruption, except to the plant or the line in which the disturbance occurs.

Or as a further expansion, a number of substations may be connected in a ring and give uninterrupted service.

Of course, this is seldom done on a commercial scale on direct-current work, due to the expense, unless the importance of the service warrants it, but the same system is widely used in high-tension alternating-current transmission and a careful study of the ring system as applied in its elementary form to D.C. work will greatly assist in understanding the action of the ring system in A.C. work where three phases, phase relations and distortions, as well as inductance and capacity effects, must be considered and are very confusing unless the elementary principle be clearly understood.

Under-current Protection.—If desired, under special conditions, most reverse-current relays may be adjusted to open the breaker when the load merely drops, instead of a full reverse, by making the contacts normally closed and using the current in normal direction to hold them open. The breaker will trip on either a fall in load or on reverse.

Over-voltage Protection.—By suitably changing the winding on a moving-coil type reverse-current relay, and connecting in series with a resistor, directly across the line, it can be made to give protection against over-voltage. Figure 77 gives the diagram of connections. As the voltage rises, it forces more and more current through the moving coil, until a prede-

termined limit is reached, when the contacts close and either open a breaker or ring a signal bell.

That such protection is necessary is shown by the fact that an over-voltage may cause considerable damage by burning out lamps or other apparatus and still the total current might not be high enough to trip an overload relay. This is especially true of small plants having a generator and prime mover whose
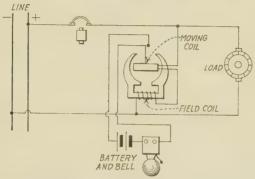
Fig. 77.—D'Arsonval type relay connected to ring bell on overvoltage.

speed may suddenly increase, thereby generating a high voltage and doing damage. The over-voltage relay gives a complete protection against this.

Under-voltage Protection.—By reversing the leads and making the voltage normally hold the contacts open, these relays can be set to close the contacts on a lower than normal voltage. While there is seldom a case where actual damage is done by under-voltage, it leads to other causes, such as excess current due to a motor stopping from lack of voltage to run it, but still having enough voltage to force excess current through it or to cause a reversal of current as in the storage battery.

If the apparatus is protected against excess and reverse current it is superfluous to connect a low-voltage relay to trip the breaker: but it is generally connected to ring a bell or give other signal that the voltage is getting low and will soon be followed by other disturbances which require opening the circuit. This allows the attendant to raise the voltage quickly or remove the cause of decrease and prevent an actual interruption.

CHAPTER VII

INDUCTION-TYPE CURRENT RELAYS

When the great possibilities of adequate protection were seen, and when it was realized that to obtain this protection a more accurate relay than the plunger type was required, the induction-type watt-hour meter was looked to as a solution of the problem. The voltage winding of the watt-hour meter was displaced by a current winding, and contacts were arranged to close when the current reached a certain value. The torque, or turning effort, of the disk was opposed by a spiral spring. The magnetic and electric circuits of a relay of the induction type are shown in Fig. 78. *A* is the main winding, and under this is another winding similar to the secondary of a transformer, which supplies the polepiece windings *B* and *D*. The path of the magnetic flux is indicated by the dotted lines.

Figure 79 shows a standard induction-type relay and Fig. 80 a schematic diagram of parts as viewed from the top. The disk *A* is damped by the permanent magnets *D*, in a manner similar to a watt-hour meter, except that both windings on the electromagnet *C* operate from the current of the line alone, as in an ammeter. Instead of the disk revolving continuously when current is applied, the rotation is opposed by the spiral spring *I* fastened with its outer end to the permanent support *E* and its inner end to the shaft *B*, which also carries the moving contact *F*.

When sufficient current flows through the electromagnet *C* to develop in the disk the necessary torque, it rotates until the contact *F* touches contact *G*, thereby completing the trip circuit.

The foregoing describes the induction-type relay without its present refinements. It had great accuracy, but one great drawback was that the moving contact "floated." That is, the load might be sufficient to turn the disk half way around, so if the relay was set to operate on 5 amp., and the load was
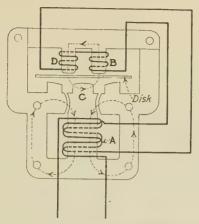
Fig. 78.—Magnetic and electric circuit of Westinghouse inverse-time-limit induction type relay.
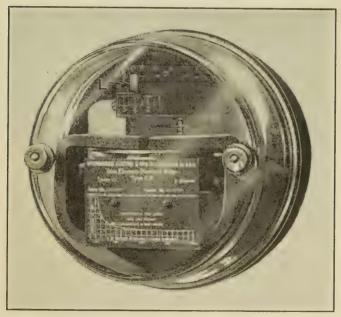
Fig. 79.—Westinghouse induction type overload relay.

4.5 amp. for some time and then suddenly increased, the closing of the contacts would be almost instantaneous, because 4.5 amp. caused the contacts to "float" near to the tripping point. To overcome this, several holes were cut in the disk, beneath the poles of the electromagnets. These holes decreased the torque considerably, but once the current became high enough to move the disk slightly, the holes were moved out from under the poles, and the latter then, acting on the solid metal, caused the disk to revolve until the contacts were closed.
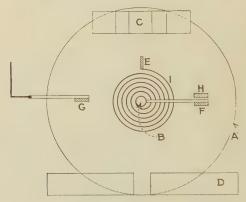
Fig. 80.—Showing position of contacts, magnets, etc. in Westinghouse relay (top view).

This insured an inverse time limit on all overloads, as the disk was always at its starting point until an overload occurred. As all circuits could not be set to trip on the same overload, taps were brought out on the current coil, which enabled the operating current to be varied over a wide range, a common range being 4, 5, 6 ,7 and 8 amp., although later practice has often shown 4 to 12 or 4 to 16 amp. preferable.

In the induction-type relay, Fig. 79, the taps are changed by inserting a screw in a marked plate, to make contact with the desired tap. The metal piece on the front of relay, Fig. 81, has a number of tapped holes to receive the screw, which may be put in any hole and make contact with the taps. The main coil is wound on the electromagnet and has the taps brought out at the correct turns to give the desired operation.

The block is of insulating material and is arranged so the taps cannot pull out.

As has been pointed out previously, it is sometimes desirable to have an inverse-time limit on moderate overloads and a definite-time limit in the case of severe short-circuits. This
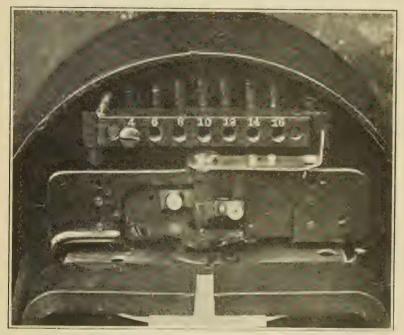
Fig. 81.—Current tap plate of Westinghouse induction overload relay.

combination of inverse time on moderate overload, gradually decreasing to a definite time on heavy overloads or short-circuits, is met in the induction-type relay by the use of a small transformer called a "torque compensator."

Torque Compensators.—This torque compensator is introduced into the secondary circuit as shown in Fig. 82. The main winding A carries the main current as in Fig. 78 and, by its transformer action, induces a current in the primary B of the small transformer. On the opposite side of the core C is the secondary D which supplies the polepieces E and E'

with the necessary current to react on the main flux, or magnetism, from the pole F produced by coil A. At moderate loads the current in D will increase in proportion to B, but the iron in C is of a cross-section such that, after the current in coil B passes a certain value, the core becomes saturated, consequently the current in D cannot increase no matter what the overload may be. Since the current in the coil cannot increase above a definite value, the torque on heavy overloads becomes constant, thus resulting in a definite-time delay.
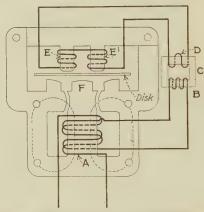
Fig. 82.—Magnetic and electric circuit of Westinghouse definite-minimum time limit relay.

It is essential in the protection of radial and ring systems that the time of the relay be variable. To accomplish this, the angle through which the contact must travel is varied. Thus, if the contact must travel one-half revolution, it may take 2 sec., but if a stop H, Fig. 80, is arranged so that the contact need make only one-fourth revolution, the time may be halved. Other positions, easily set by a small lever, enable any time from instantaneous to a maximum to be readily set.

A typical curve for an overload-induction relay is given in Fig. 21, reference to which will show that 150 per cent load takes about 10 sec. for the relay to close its contact; 200 per cent load requires about 5 sec.; 500 per cent, 2.75 sec.; 1,000 per cent and any overload in excess of this take a definite time of about 2 sec. These values are taken at the hightes

time setting; if the setting is halved, the time is halved.   In other words, the time is almost proportional to the lever settings.

Relay Contacts.—Owing to the accuracy required in a protective relay, the parts must be small and delicately constructed. Consequently the contacts of the trip circuit cannot be large and bulky, and are not designed to open the trip circuit either intentionally or unintentionally, once it has been established. This is one point that requires careful consideration in the design or selection of a relay, as the tripping circuits are, as a rule, highly inductive, and an arc which would naturally follow the opening of the circuit might persist for a considerable length of time and result in serious burning of contacts.   For this reason it is necessary that the tripping circuits be opened by an auxiliary pallet switch or contacts fastened to the circuit breaker in such a manner that the opening of the breaker automatically opens the tripping circuit.

Contactor Switches.—There are two reasons why the contactor switch is required.   In the first case, take for instance a circuit breaker which requires 0.2 of a second to open after the relay contacts have closed and the trip coil of the breaker has been energized.   Suppose that the overload on the line should disappear in the small interval between the instant of contact closing and the opening of the breaker.   The relay would instantly attempt to reset and in doing so would open the circuit before the auxiliary pallet switch opened it, thus resulting in severe contact burning.   The contactor switch overcomes this.

In the second case, the overload might just be great enough to barely close the contacts.   This weak closing might not allow sufficient current to pass through to operate the trip coil of the breaker and the contacts would "chatter" and burn badly.

To overcome this, the contactor switch may be employed to change a weak fluttering contact into a good positive contact which will keep the trip circuit closed in the relay until it is opened externally by the pallet switch on the breaker.

A diagrammatic scheme of the old style contactor switch is shown in Fig. 83 while a diagram of the modern contactor switch is shown in Fig. 84.   In both these figures, the main relay contacts *A*, when they close the tripping circuit of the relay, energize a small coil *B* that attracts an iron armature or plunger *C* and

closes the contacts *D*, which are in parallel with the main con-
tacts *A*. Thus it will be seen readily that even though the
contacts *A* should open, the current will pass through *B* and con-
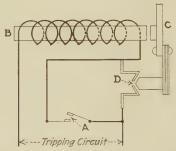
Fig. 83.—Schematic diagram of obsolete contactor switch.

tacts *D* will stay closed until the pallet switch on the breaker
opens the circuit; when this occurs coil *B* will lose its pull and
open contacts *D*. This contactor switch will close about 20
amp. at 220 volts.
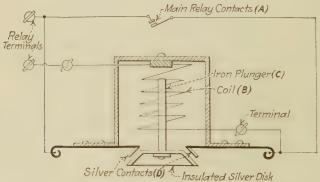
Fig. 84.—Schematic diagram of modern contactor switch.

In Fig. 85 is shown a view of the assembled contactor switch
and also an exploded view showing the plunger and contacts.
This contactor switch is usually mounted in the bottom of the
relay as shown in Fig. 86.

If the trip circuit requires more than the current which can be
safely handled by the contactor switch, then an auxiliary relay
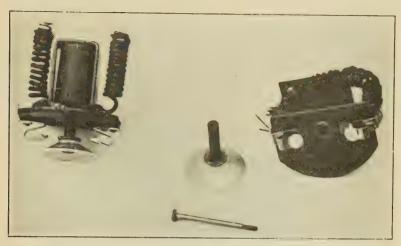
Fig. 85.—Assembled and exploded view of Westinghouse contactor switch.

Fig. 86.—Showing contactor switch and curve plate.

such as shown in Figs. 195 and 196 may be used.   The auxiliary
relay shown in Fig. 197 not only handles greater current, but
may also be arranged to trip several circuits upon the function-
ing of one relay.

Continuity Indicator.—One difficulty frequently encountered
is the burning out of trip-current-carrying springs due to excessive
trip currents or contact arcing.   To overcome this, special con-
tacts may be arranged as in Fig. 87 to prevent the spring from
carrying any current.   Contact *A* is stationary while *B* is
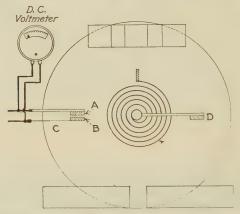
Fig. 87.—Special arrangement of contacts when required with continuity
indicator.

mounted on a thin flexible strip *C*.   Then when the disk turns,
the arm *D* strikes the contact *B*, forcing it against *A* and com-
pleting the trip circuit.

Some companies connect a small voltmeter or a pilot lamp
across the contacts as in Fig. 87 in order to tell by its continuous
indication that the trip circuit is alive up to the contacts.   Should
the meter fail to indicate or the pilot lamp go out, the operator
knows immediately that the trip circuit has failed.   In other
cases, a small telegraph relay is connected to ring a bell when the
circuit fails.

Another later form of continuity indicator or "supervisory
circuit" is formed in this relay by adding a second spiral spring
and using the standard relay with its current-carrying spring and
moving contacts.   The voltmeter or pilot lamp is connected to

feed through both springs, so if the main spring burns out, then the continuity indicator indicates by the pilot lamp going out.

The General Electric Induction Relay.— A front view of this relay is shown in Fig. 88 where the external similarity to the house-type watt-hour meter is readily apparent. From the schematic diagram of the front mechanism as shown in Fig. 89 it will be seen that there is a disk *A* which is driven by a U-shaped
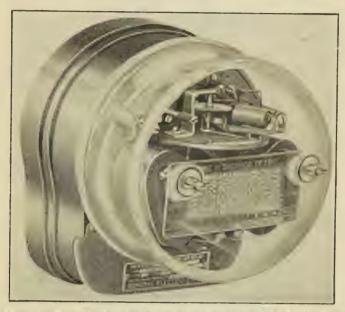
Fig. 88.—The General Electric Co. induction type overload (excess current) relay.

electromagnet (not shown) and which is damped by the permanent magnets *C*. Upon the occurrence of an overload the electromagnet causes the disk to turn against the restraining action of the spring *U*. It will be noted that the edge of the disk is slotted with slots of decreasing depth, so that as the disk revolves, more and more metal is placed under the action of the driving magnet, thus resulting in an increased torque which offsets the increasing restraining action of the spring and prevents the disk from floating.
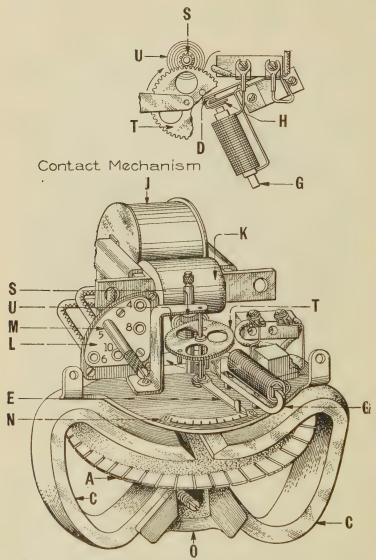
Fig. 89.—Schematic diagram of G. E. induction type overload relay.

The pinion S causes the gear to revolve, and as soon as the disk revolves far enough, a pin on gear T pushes the contacts D together, thus completing the tripping circuit.

In order to prevent the contacts from fluttering or opening the trip circuit and causing the contacts to burn, the electromagnet G is connected in series with the trip circuit and arranged so that the first flutter of current which passes through the trip coil energizes the electromagnet, which quickly attracts the iron armature on contacts D and holds them positively shut until the trip circuit is opened by the auxiliary pallet switch on the circuit breaker.

Time-Load Curves.—It has previously been shown why a definite or inverse-definite time delay was preferable to a true inverse time delay where the curves may intersect at extremely
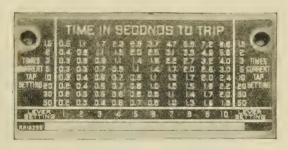
Fig. 90.—Index plate of G. E. induction overload relay.
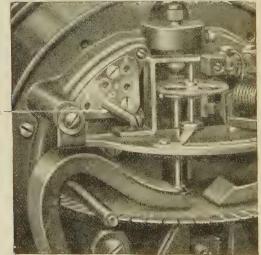
heavy overloads. In this relay, this inverse-approaching-definite minimum delay is obtained by using a small saturation transformer connected so that its primary carries the line current and its secondary feeds the driving electromagnet. At high currents, this transformer limits the current supplied to the driving electromagnet and results in curves as shown in Fig. 22. It will be noted that although the time is slightly inverse throughout the entire length of the curve, yet the curves never intersect and are clearly distinguishable even at 5,000 per cent of normal load. This overload is seldom met in actual practice except on very exceptionally heavy short-circuits.

Practice has shown on this relay that a table of figures is preferable and more easy to interpret than a set of curves. Consequently, the relay is provided with a tabulated nameplate

as in Fig. 90 which is self-explanatory from a careful study. If desirable, a transcript plate may be made in which the actual transformer secondary operating currents are tabulated instead of

		AMP. RATING OF TAP					TIME IN SECONDS									
		4	5	6	8	10										
	15	6	7.5	9	12	15	0.9	1.4	2.0	2.6	3.2	3.7	4.3	5.1	5.9	7.0
	2	8	10	12	16	20	0.8	1.1	1.5	2.0	2.4	2.9	3.3	3.8	4.4	5.2
CURRENT SETTING	3	12	15	18	24	30	0.6	0.9	1.2	1.5	1.8	2.1	2.5	2.9	3.3	3.9
	5	20	25	30	40	50	0.5	0.7	0.9	1.2	1.5	1.7	2.0	2.3	2.7	3.1
TIMES TAP SETTING	10	40	50	60	80	100	0.4	0.6	0.8	1.0	1.2	1.4	1.8	1.9	2.2	2.5
	20	80	100	120	160	200	0.4	0.5	0.7	0.9	1.1	1.3	1.5	1.8	1.9	2.2
	30	120	150	180	240	300	0.3	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.1
	50	200	250	300	400	500	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.5	1.7	2.0
SECONDARY CURRENT IN RELAY							1	2	3	4	5	6	7	8	9	10
							LEVER SETTING									

Fig. 91.—Operator's transcript of index plate.

using multipliers. Such a transcript is shown in Fig. 91 and is often of great convenience when changes in settings must be quickly made.

Current Tap
Plug in 10 Amp.
Hole

Fig. 92.—Location of the current tap plate in the G. E. induction overload relay.

Time Settings.—The time is readily controlled by a small lever *E* (Fig. 89) which moves over a divided scale *N*. For instance if the relay takes 2 seconds at a certain load with No. 10

setting, then at the same load it will take 1 second at No. 5 setting, or 0.2 seconds at No. 2 setting, etc.

Current Tap Plate.—A close-up view of the current tap plate is shown in Fig. 92. This plate contains taps from the primary coil of the saturation transformer and is arranged to keep the ampere turns constant. In changing taps, an extra plug is screwed into the desired hole and then the first one removed. Two plugs must never be left in at one time as this would short-circuit part of the transformer primary; nor must both plugs be withdrawn at once as this would open-circuit the series line transformer and might result in a dangerously high potential at the relay terminals. The numerals 4, 5, 6, 8, and 10 represent the minimum values of current in amperes that each tap requires to cause the relay to close its contacts.

Adjustment of Tripping Current.—Although every relay as it leaves the manufacturer is carefully adjusted to trip on its rated current, yet due to variation in wave form, or frequency, or shocks in transportation it will sometimes be found that the relay requires slight adjustment. For this purpose, a flux shunting screw is conveniently located on the lower left hand side. Loosening the lock nut and turning the screw to the right increases the current required and turning to the left decreases it. After adjustment the screw should again be locked by the nut.

Relation of Various Parts.—When the relay has been repaired or reassembled it is necessary to see that the first short slot in the edge of the disk stands just under the front edge of the opening in the left-hand frame. This is to insure against "floating" of the disk at low overloads.

The time lever must be set on zero and then the contacts adjusted so they are barely closed. When free, these contacts should be separated from each other by about $\frac{3}{64}$ inch.

In these relays will be found a black spot painted on the edge of the disk (as in Fig. 93) and this spot should come exactly in the center line of the bracket which supports the permanent magnets.

With the time lever set on zero of its scale the contact mechanism is brought into position for assembly with the relay frame, and the holding screws partially set up, leaving the gear and pinion disengaged. The disk is then rotated carefully in a

counterclockwise direction (looking down) from its free position
through approximately $\frac{7}{8}$ of a revolution until the spot painted
on the edge of the disk is midway between the pole tips of the
permanent magnet.   The gear and pinion are then engaged and
the mechanism secured by tightening the holding screws.   Care
must be taken that the gears are not meshed too deeply.   There
should be a little play in them when the disk is held fixed and the
gear wheel shaken back and forth.

Contacts
Closed

Time Lever
on 0

Slots in
Disk

Black Spot
on Center
of Magnet,
Supports
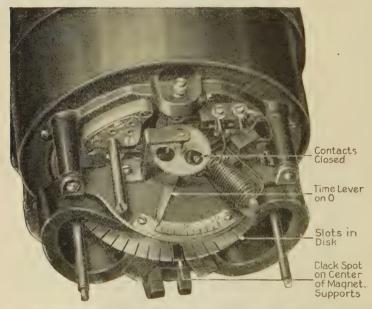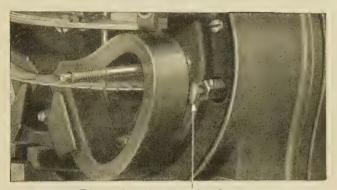
Fig. 93.— Showing the correct relation between contacts, time lever and black
disk spot in the G. E. induction overload relay.

The correct location of the driving magnets is also important·
Both the upper and lower pole pieces have a secondary conductor
or shading ring and the angular position of the pole pieces with
respect to the radius of the disk at their center determines in
a large degree the torque exerted by the disk when a given current
is applied to the relay windings.

The upper pole piece is secured to a pin in the U-shaped
driving magnet in such a manner that it can rotate slightly as the

temperature compensating strip is attached to it and thus is enabled to keep the torque constant regardless of changes in ambient temperatures. The compensating strip may also be moved if desired by means of the "Temperature Compensator Screw" shown in Fig. 94.

The lower pole piece is rigidly secured to the driving magnet and this adjustment should not be disturbed.

Temperature Compensator Screw

FIG. 94.—Showing the position of the temperature compensating screw in the G. E. induction overload relay.

The permanent magnets on the front of the relay serve as a damping or retarding element for the disk and they may be moved in or out to vary the time delay of the relay. The general practice is to set these magnets so that when the time lever is set on 10, and applying 80 amp. to the 4-amp. tap, there will be a time delay of 2.2 sec.

If, for any reason, these magnets must be removed, a mark should first be scribed on the face of the bracket to act as a guide in accurately relocating the magnet, when it is replaced.

It is important to note in changing magnets that they should never be set out so far that the inner end of the slots in the disk will pass at any part of the disk travel very near to the outer edge of the permanent magnets. If set further out than this, the time of operation will be decreased instead of made longer. In other words, the point of greatest retardation is obtained when the outer edge of the permanent magnet is about $\frac{1}{8}$ inch inside of the lower end of the slots in the disk.

6

When replacing the time index plate be sure that it is adjusted so that its back does not touch the edge of the disk.

INDUCTION VS. SOLENOID-PLUNGER RELAYS

There are a number of disadvantages in the solenoid-plunger relays which are not present in the induction type. In the air-bellows lagged type, the time is very inaccurate and unreliable, due to the drying out of the leather.

Another difficulty is that the continuous vibration to which they are subjected gradually loosens the nuts, screws, etc., unless the relay is unusually well built. The noise is also objectionable. The force on the plunger increases as the square of the current, with the result that the forces reach such enormous values during a heavy overload that the leather may be stretched or even burst. It is no uncommon thing for relays of this type to be so badly damaged that they will fail to operate the next time another short-circuit occurs.

The definite-time-limit relays are not subject to such defects in the bellows due to overload, but their inherent variation in time makes them unreliable for selective action closer than about one second. Another disadvantage of bellows type relays is that, once the core is lifted, then in order to reset, the current must drop to 40 or 50 per cent of the minimum tripping value.

The oil-damped relays are not at all permanently accurate and change in time greatly due to changes in the viscosity of the oil upon changes in temperature.

An objection to the use of all solenoid-plunger relays is that the expense of adjusting them for accurate work is often greater than the cost of the relays themselves. It is possible that an automatic sectionalizing scheme could be laid out so that time limits varying by steps of 1 to 2 sec. could be used, in which case the bellows type of relay might be sufficiently accurate, but such accuracy could not be obtained except at considerable expense. In order to adjust relays of this type it is generally necessary to disconnect them from the circuit and connect them to a test circuit, which in many cases is not easy to obtain. In addition, a chronograph, ammeter and control device are necessary. Needless to say, such a calibration must be made by a skilled

tester. If a change in the time limit is later required it is necessary to repeat the entire process.

The best feature of the induction type of overload relay is its remarkable accuracy and permanence of calibration. The use of permanent magnets as a time-limit device prevents overswinging and chattering of the contacts, and the construction is such that the relay will instantly cease its movement when the overload disappears. There is no possibility of mechanical injury due to excessive currents when the torque compensator is used, because the saturation of the iron prevents the mechanical forces from increasing beyond a certain amount.

The current and time adjustment of the induction relays are plainly and accurately marked and any desired change can be made at a moment's notice. This is a feature much appreciated by the operating man who is responsible for the successful operation of the automatic-sectionalizing devices on his system. He can personally check the setting of every relay and thus be sure that no incorrect operation will result due to the carelessness or incompetence of an assistant.

Load on Instrument Transformer.—When selecting a relay for use on current transformers which also operate instruments, it is important to consider the load which the relay places on the transformer. The induction type of relay requires a smaller amount of energy than does any other type, a feature to be appreciated when bushing-type current transformers are used.

Relay Specifications.—In order that unreliable and unsatisfactory overload and underload relays may not be used in installations, it is always well to add the following specifications. If a relay meets these fundamental requirements and is well constructed, it should be satisfactory, but these specifications will bar the undesirable relays.

"Overload-protective relays shall be equipped with a time limit that varies inversely with the current at all moderate overloads and which will not drop below a definite minimum time at extreme overloads. The definite minimum time limit shall be adjustable for all values between 0 and 2 sec. (or 0 and 4 sec.), which adjustment shall be accurate and permanent. The relays shall be calibrated at the factory, and the calibrating data shall be fixed to the front of the relay. It shall be possible

to make, without the use of any testing equipment or timing devices, independent adjustment of both the time limit and the overload value at which the relay will operate. Relays shall be so constructed that they will not be damaged or their calibration affected by the maximum current that the generating equipment can deliver to them. Their construction shall be such that in case an overload ceases before the relay contacts have been closed, the relay will instantly commence to reset to its starting position. The energy that the current transformer must furnish to operate a relay shall not be in excess of 20 volt-amp."

CHAPTER VIII

A.C. POWER-DIRECTIONAL RELAYS

In the transmission of electric energy, there is perhaps no more important piece of apparatus than the power-directional relay which is used to discriminate or localize and isolate a defective feeder or substation and thereby secure a maximum of continuous service. These relays are frequently called "reverse-current" relays, "overload and reverse-current" relays, "reverse-power" relays, and "reverse-overload relays." Although quite good protection has been obtained by the use of split-conductor and pilot-wire systems for the protection of parallel feeders, (as will be described later), yet such systems are very expensive
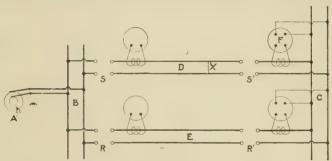

Fig. 95.—Showing why the current reverses when one "parallel feeder" is shorted.

to install and maintain. Their greatest excuse at the time of installation was the lack of a reliable power-directional relay as it must be admitted that the early relays were quite lacking in some points, and since the perfection of the present-day power-directional relays, the pilot-wire and split-conductor systems are used only on certain systems, where careful design and calculation indicates a distinct advantage.

The development of a satisfactory power-directional relay, however, was by no means a simple proposition. In order to better illustrate this, it may be well to consider some of the early forms and show why they failed.

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A review of the most common use of the power-directional relay is shown in Fig. 95, where A is a generator feeding the bus B, which supplies the sub-bus C over the parallel tie lines D and E. Suppose a short-circuit occurs at X on feeder D. Current will feed into the "short" X, directly from the bus B and also over the line E, through C and into X. But it will be noted that while the power flow in feeder E and in feeder D as far as X is in the normal direction, yet the power flow in the section of the feeder D between X and C has reversed. Or in other words the current (instantaneous values) has reversed its polarity with respect to the voltage (instantaneous values). This reversing of respective instantaneous polarities of current and voltage is responsible for the term "reverse current."

It might appear, at first thought, an easy matter to place contacts on a wattmeter, which would hold open on normal direction, and close on reversal of power. But should the "short" be near the substation, the voltage will be very low, although the current may be high, and the power actuating the wattmeter will be extremely low in this case. In fact, in some tests made, where the line was actually shorted intentionally, it was shown that the voltage may drop as low as 1 per cent of normal.

Further, we are usually dealing in actual practice with three-phase current, and phase distortions must be considered, particularly in the case of short-circuits from one line to ground, or on one phase only. These short-circuits may so distort the relation of current to voltage as to cause the angle between them to be almost 90 deg., and consequently there is the worst condition for low torque in the wattmeter element, *i.e.* very low power factor and very low voltage.

Still, one of the first relays used for reverse-power tripping had a wattmeter element which closed contacts on reversal of power. In this form, the movement was the same as the induction wattmeter. There was a movable arm and contacts and two stationary contacts, one on each side of the movable contact, with separate adjustments provided to allow different settings for tripping points in normal and reverse directions. The movement was controlled by a strong spring to allow set-

ting to two or three times full load. No attempt was made to introduce time lag, or damping, the relays acting instantaneously.

These relays were found to be entirely inadequate on account of insufficient torque when short-circuits caused the voltage and power factor to drop to low values. They proved conclusively that a pure "wattmeter" relay was not satisfactory.

Another early relay used a moving coil dynamometer-type movement with an ironclad magnetic circuit to increase the torque. One particular reason why this failed was because the very powerful current in the current coil generated a voltage in the voltage coil of the relay during a short-circuit and consequently the relay would not trip when it should. Under other conditions, the induced voltage caused it to trip when it should not.

Another disadvantage of the instantaneous reverse-power relays was that sudden momentary surges, such as might be due to synchronizing or switching, would trip out the breaker unnecessarily.

There were many attempts made to add corrective features to the early wattmeter relays. One of the most interesting was an arrangement consisting of a contact device in combination with a quick-acting regulator to maintain the current practically constant in the potential coil regardless of low voltage. Adjustments were provided to vary the time element of the relay.

The next step in development was the "differential" type, in which a voltage coil was added to "polarize" an ordinary current-operated relay, in order to cause the relay to operate at a lower value of current in the reverse than in the normal direction. Such relays were made in both the solenoid-bellows type and the induction type. In the solenoid type, a voltage winding was superimposed upon the current solenoid: voltage and current acting in opposition on normal flow, and acting additively if the power flow reversed.

Another form of this differential class of relay was made on the induction-type wattmeter principle, by winding the relay for excess current and adding a voltage winding connected to a voltage transformer.

The coils were wound on the iron laminations in such relation

as to cause the torque in the movable disk to be proportional to the square of the current; a terminal block was used to vary the current settings by changing the number of turns in the main coil. When voltage was applied to the terminals of the main coil, the effect was to shift the torque curve in the reverse direction. It will be understood that the great advantage of this type of relay over the earlier wattmeter types was that even should the voltage or the power factor, or both, fall to zero, the relay would become a plain "excess-current" relay, and thus trip out the circuit breaker. Whereas the wattmeter relays would be inactive under these conditions, resulting in no automatic protection, and these relays would trip. Their difficulty, was, of course, that under such conditions they could not discriminate between directions of power flow and thus would trip out both circuit breakers at the substation ends of parallel lines. But they were better than relays which under conditions of low voltage or power factor would not trip out at all, and they were thus used satisfactorily for a number of years.

These relays were also made for polyphase work with two movements operating one shaft and contact, but as the tripping values would be different, according to whether the overload was on one phase or on more, they were abandoned in favor of the use of separate single-phase elements for polyphase service.

As regards their place in the field, these "overload and reverse" relays can only be regarded as a modification of "overload" (excess-current) relays, which, with given conditions of superimposed voltages as regards value and direction, will trip at different values of current.

They become practically "current" relays when the voltage drops very low.

REQUIREMENTS OF A PRACTICAL POWER-DIRECTIONAL RELAY

From the foregoing it is evident that a practical power-directional relay should fulfill the following conditions:

1. It should close its contacts positively when the direction of power flow is reversed, under all possible conditions of voltage, power factor and current.

2. It should never, under any circumstances, close its contacts when the direction of power flow is normal.

3. The excess current and the directional element must be mechanically separate so that the directional element has no influence on the characteristics of the excess-current element, but merely determines if this excess current is in the "normal" or "reverse" direction.

These are the fundamental requirements. In addition it is desirable to have a time element which can be accurately predetermined and quickly adjusted to any desired value.
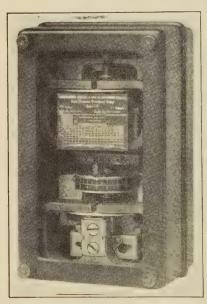
It is assumed, as a matter of course, that the relays are reliable and rugged in their mechanism, and have the necessary current-carrying capacity both in windings and contacts. These two requirements immediately eliminate all relays having mutual inductance between the current and voltage coils such as the dynamometer type has at present.

A most important step toward fulfilling these conditions was in adding a separate wattmeter element with contacts in series with those of the excess-current relay. The wattmeter element was very carefully constructed, with a weak spring and quick time element, so that the least flow of current in the reverse direction would close the contacts and thus allow the excess-current relay to trip the breaker, in the event of excess current in the reverse direction. With current in the normal direction, the wattmeter contacts remained open, so that even should an excess current cause the excess-current relay contacts to close, it still could not trip the breaker, because the wattmeter contacts were in series with excess-current relay contacts and the breaker could not trip until both contacts closed: *i.e.* an excess current in the reverse direction only and never in the normal direction. This combination clearly selected between an overload in the normal and reverse direction even if the voltage dropped to 2 per cent of normal and the power factor to 10 per cent.

LATEST DEVELOPMENTS

In Fig. 96 is shown one of the most highly developed types of power-directional relay on the market today. This relay combines all the points heretofore mentioned and has so far met the most exacting conditions of parallel feeders, ring systems and networks of the heaviest and most intricate power systems of the country. It will be noticed that the single case con-

tains two separate induction elements, each with its windings, disk, magnets, contacts, etc. There is no mechanical connection whatever between the two moving elements. The top element is the quick-acting extremely sensitive watt element and the lower element is the standard "excess-current" (over-
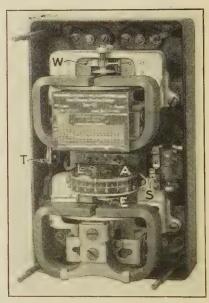

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Fig. 96a.   Fig. 96b.

Fig. 96a.—External view of Westinghouse power directional relay.

Fig. 96b.—Internal view of Westinghouse power directional relay.

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load) relay, provided with adjustable time lever, etc. exactly as described for the overload inverse-definite-minimum time-limit relay.

Figure 97 shows the internal wiring diagram of connections, the current winding being shown by the heavy black lines. Figure 98 shows the same connections but the voltage circuit is this time shown by heavy lines, and Fig. 99 shows the same, with the trip circuit shown heavy.

The Contactor Switch.—Another effect present during short-circuit was that, due to the flow of heavy currents, the vibration of the disks prevented the making of good contacts at the watt element and also caused the disks to slip on the shafts due to the
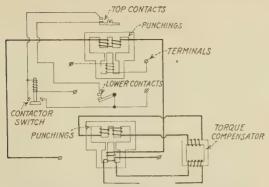
Fig. 97.—Internal diagram of Westinghouse power directional relay with series circuit shown with heavy lines.
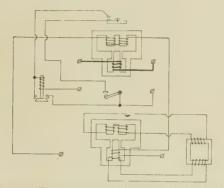

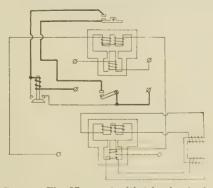Fig. 98.—Same as Fig. 97 except with potential circuit shown heavy.

Fig. 99.—Same as Fig. 97 except with trip circuit shown heavy.

excessive torque developed. The vibration effect was a matter of magnetic attraction between the series coils and the induced currents in the disk.

Fortunately, this weak, fluttering contact may be changed into a good positive contact by means of a contactor switch, mounted in the case. This consists of a solenoid, capable of attracting an iron plunger which carries a silver contact, as in Fig. 84.

Now suppose the main-relay contacts just barely close and are vibrating or chattering violently due to the heavy, induced currents in the disk to which they are attached. Their partial touching allows a weak, fluttering current to flow in the solenoid. This weak current immediately raises the plunger, and the contact disk immediately short-circuits the two stationary contacts, which, being in parallel with the main contacts, immediately take all the trip current by making good positive contact, thus positively energizing the trip coil and tripping the breakers.

It is very evident that should the main contacts still flutter, there will be no spark, and in fact, after the first touch they may even open, although the touch was enough to close the contactor contacts and trip the breaker. The trip circuit will stay energized, and these contacts will stay closed until the circuit is opened by the auxiliary-pallet switch on the breaker, which is arranged for this purpose.

The contactor switch not only assures positive contact, but by increasing the tripping-circuit capacity from 2 to 20 amp., avoids the use of an auxiliary-relay switch, except in the case of very heavy trip currents.

The Torque Compensator.—The effect of the excessive torque loosening the disks on the shafts was easily overcome by means of the "torque compensator," which, as was thoroughly explained under "Induction-type Relays," is merely a small transformer with the primary carrying the main current, the secondary supplying the relay windings, and so proportioned that the iron becomes saturated at heavy overloads, thus preventing excessive flow of current in the relay.

Stray Fields.—In view of the fact that the heavy overload currents produce such a strong field, it might be suspected that this alternating field would weaken the permanent magnets

and change the time.   This, however, is not the case, as the magnets are placed on the diametrically opposite side of the disk from the driving coils, and thoroughly shielded by the framework exactly as in a watthour meter.

Moreover, in testing, the relays are subjected to many times more current than they would ever get in actual practice, so any demagnetizing effect would make a permanent change the first time the relay was tested and any following excess current could not possibly damage its action.

Fɪɢ. 100.—G. E. power directional relay.

Other Relays.—Instead of combining a watt element and an overload relay in one case, and using three combination instruments on each three-phase line, some engineers prefer to house the three watt elements in one case and use this relay in conjunction with two or three overload relays, either plunger or induction type.   Such a relay is shown in Figs. 100 and 101. In Fig. 102 is shown the internal wiring diagram.
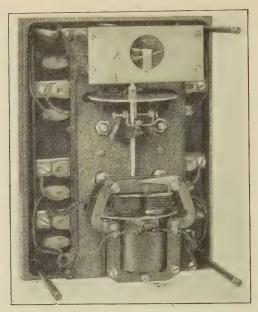
Fig. 101.—Interior view of G. E. polyphase power directional relay.
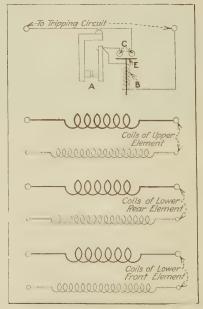

Fig. 102.—Internal wiring diagram of G. E. polyphase power directional relay.

From this it will be plainly seen that there are three separate current coils and three separate potential coils, and since the relay operates on the induction principle, there is no mutual inductance between coils; consequently no induced voltage in the potential coil from the heavy current flowing in the series coil.

Two disks are used, the upper one of which is driven by one element. The lower disk is driven by two elements, one in the front (plainly shown in Fig. 101) and one in the rear. Under normal direction of power, the disks tend to rotate in one direction and keep the contact open. Reversal of power flow causes the disks to rotate in the opposite direction, thus closing the contact. Since the action desired is as nearly instantaneous as possible, no attempt is made to damp the movement; the arc of disk travel is very small.

Fluttering trip currents such as might be due to vibration of disk, bouncing of contacts, etc. are quickly transformed into full-strength current by means of the small auxiliary contactor switch.

Power-directional Multi-element Relays Used with Overload Relays.—This power-directional relay must be used in conjunction with a three-phase or three single-phase overload relays such as the induction type or solenoid-bellows type, to secure proper protection.

The trip circuits of the overload relays (connected in multiple) are connected in series with that of the power-directional relay, so that neither can trip the breaker separately, but both must close their contacts before the breaker will be tripped.

Each overload relay is connected in series with a current coil of the reverse-power relay. The complete connections of a three-phase circuit are shown in Figs. 148a and b. This plainly shows the main three-phase line, protected by breaker, and supplied with three current and three voltage transformers. Each current transformer supplies one current coil in the power directional relay and one overload relay. The trip of the power-directional relay is connected in series with the trips of the overload relays and operates the trip coil of the breaker. When the breaker opens, the auxiliary switch opens, thus resetting the contactor switch in the power-directional relay.

Differential Power-directional Relay.—Another recent development is the differential power-directional relay. This must be used in conjunction with the auxiliary relay shown in Fig. 103.

This relay is also shown with the cover removed in Fig. 103 and the diagram of connections is shown in Fig. 164. The power-directional relay is arranged to make contact when it moves either to the left or right. But once it closes one contact, it instantly energizes one of the interlocking relays and this relay opens the
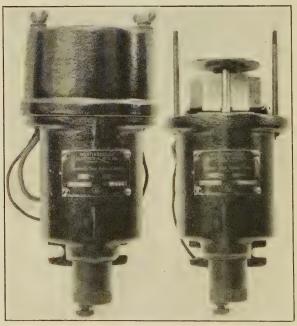

Fig. 103.—Westinghouse auxiliary interlocking relays with and without protecting cover.

trip circuit to the opposite contact. The interlocking relay resets in about two seconds after the trip circuit has been de-energized by the opening of the circuit breaker.

The applications of power-directional relays to various systems will be discussed in a subsequent chapter devoted to that subject.

Specifications.—In order that engineers may obtain the highest grade of power-directional relays and to guard against the use of obsolete and defective-principled relays

it would be well for engineers and architects to include the following in their specifications: "Power-directional relays should consist of two separate and complete elements, one which operates on excess current, as described hereafter, and one which operates on a reversal of power as described hereafter. These elements may or may not be mounted in the same housing. The current element shall be equipped with a time delay that varies inversely with the current at all moderate overload and which becomes definite at heavy overloads. This definite time shall be adjustable for all values between 0 and 2 sec. (or 0 and 4 sec.) which adjustment shall be accurate and permanent. The relay shall be equipped with a convenient terminal board by which the current values for tripping may be adjusted easily to a number of different values, say 4, 5, 6, 7 and 8 amp. for instance.

"The element which operates on reversal of power shall be selective with regard to direction of power flow under all conditions of low power factor and unbalanced short-circuits, and shall be selective at 2 per cent of normal voltage upon the occurrence of an overload of 300 per cent or more. They shall be so constructed that the normal power, including moderate overloads, can flow in either direction through the circuit to which the relays are connected, without causing the relays to trip the circuit breaker."

This specification of course, is in addition to the regular specifications covering workmanship, material, etc.

CHAPTER IX

CHARACTERISTICS OF A.C. DISTURBANCES

Many of the early protective relays were designed with but a partial knowledge of the actual characteristics of the electrical disturbances which they were supposed to detect and isolate. Consequently, there were many failures under certain conditions, and these failures led to an intimate study of the effects of an electrical disturbance from both a theoretical and an actual standpoint. In some instances, the lines were actually shorted at various locations to determine the actual conditions, while in other cases, miniature systems were built, with lines having characteristics similar to the main line, in order to study the extent and divisions of overloads.

Even the protection of simple apparatus such as motors and transformers requires an intimate knowledge of how certain apparatus acts in case of electrical distress.

Some of the more important points on which an accurate knowledge must be obtained are as follows:

1. What is the intensity of a "short-circuit"?

2. For how long can the overload exist?

3. What is the effect on the system voltage?

4. What other effects, such as phase distortion and surges, accompany severe disturbances?

5. What must the relay do and what must it not do, and what are the best connections?

These points are essential, not only to the user of the protective relays, but also to the manufacturer, and it is safe to say that had the manufacturers had proper information on these points when they designed their first relays, the relay user could have saved many thousands of dollars of damage to apparatus and avoided thousands of interruptions.

EFFECTS OF OVERLOAD

The duration of an overload without damage depends entirely on the apparatus itself; that is, it may be sustained until the excessive heat starts to burn the insulation, or cause other

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effects which would lead to damaged insulation. Damage from overload is seldom caused except by heat, some exceptions being the breaking of shafts or the explosion of transformers, or the puncturing of insulation due to surges. Modern design has, however, practically eliminated this danger.

Some motors may often have their voltage reduced to zero for a second or so without being damaged or losing their load; they also may carry overload (about 50 per cent) continuously without serious damage; but they must be protected so that they will be cut out of service should the load exceed 150 per cent for any length of time. If internal short-circuits develop, causing excess current, they must be cut out very quickly to avoid serious burnouts.

Power transformers must also be protected against internal and external overloads in the same manner; in fact, an internal short in a large transformer might damage it severely in a few seconds, and as an internal short will seldom clear itself, its automatic isolation should be practically instantaneous.

Transmission lines are often damaged by prolonged overload, and they also cause an excess current in the generators to which they are connected in case of short-circuits.

One of the big present-day problems in automatic sectionalizing is to cut out a short-circuited section of line before it burns down.

The overload which an alternator can stand depends entirely upon the alternator, as the characteristics of such machines vary over a wide range. The short-circuit current may be roughly calculated by observing the voltage drop between the two sections at normal load, as will be explained later.

The current during a short-circuit decreases very rapidly until a sustained short-circuit current is reached, as will be seen by referring to Fig. 104. This curve does not mean that the maximum possible short-circuit current is 100 per cent, but take as example an alternator which gives 12 times the normal load current on short-circuit. This is 100 per cent, but this 12 times quickly decreases until the sustained current is about 12 per cent of 12 times or 1.4 times the normal load.

Some alternators may deliver a sustained short-circuit current of two and one-half or three times the full-load current.

This rapid decrease of short-circuit current is another important reason why a breaker should not trip out instantly. Its breaking capacity must be considerably greater to trip instantly than to trip when the current falls to its sustained value, which is much lower.
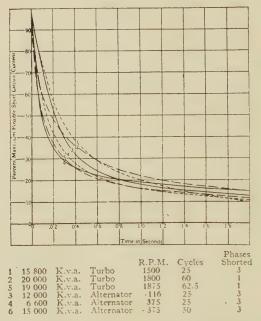

				R.P.M.	Cycles	Phases Shorted
1	15 800	K.v.a.	Turbo	1500	25	3
2	20 000	K.v.a.	Turbo	1800	60	1
5	19 000	K.v.a.	Turbo	1875	62.5	1
3	12 000	K.v.a.	Alternator	·116	25	3
4	6 600	K.v.a.	Alternator	375	25	3
6	15 000	K.v.a.	Alternator	·375	50	3

Fig. 104.—Current decrease on asymmetrical short-circuits.

NATURE OF SHORT-CIRCUITS ON TRANSMISSION LINES

When making current calculations it should always be assumed that a short-circuit is due to a metallic connection between the conductors. On a high-voltage aerial line using wooden pins and crossarms, it sometimes happens that an insulator is broken, with the result that the wood is gradually heated by the passage of the current through it until it finally bursts into flame, thus causing an arc between conductors. A little consideration shows that the flow of the current is small until the arc is established, and that it is absurd to speak of automatically disconnecting a section of line which has such a high-resistance short-circuit. It has sometimes been assumed that

an arc has a high resistance, but this is not the case, and in general the presence of an arc at the point of short-circuit will not decrease the short-circuit current by more than a few per cent. Incidentally, it may be of interest to note that on a high-voltage ungrounded-neutral system the capacity current to ground through an arc may be greater than it is through a direct ground. There is only one case where a short-circuit is likely to increase in intensity as it develops, and that is on a system where the neutral is grounded through a resistance; a cable breakdown, for instance, frequently occurs first between one conductor and the sheath and the current flow may be limited by the neutral resistance; the trouble will quickly involve all the conductors in the cable, resulting in a heavy short-circuit, but it is possible that it will require an appreciable time to do this, in which case the relay operation may be unsatisfactory. This is particularly liable to happen if the neutral is not grounded at every substation.

CALCULATION OF THE SHORT-CIRCUIT CURRENT

In applying any protection scheme, it is necessary to determine the short-circuit currents which may develop under all conditions. It is unfortunate that the term "overload" has come into use in connection with sectionalizing distribution systems, because it implies that the relays should be set to operate at a value determined by the normal load on the feeder.

Such a setting is possible if definite-time-limit relays are used, but where a relay having inverse-time characteristics is used it is necessary to consider the current that occurs during times of trouble, and that may be tens or even hundreds of times greater than the normal current. An approximate method of determining the possible short-circuit current is by observing the voltage drop between two stations at normal load. Short-circuit current $= \dfrac{\text{normal voltage}}{\text{voltage drop}} \times$ load current.

For example, if a certain load current causes a drop of 5 per cent in voltage between a generator station and substation, the maximum short-circuit current would be 20 times the load current. Results obtained in this way are likely to be too large, particularly on lines having high inductance.

The calculation of the short-circuit currents on a complicated system involves more or less approximation, and a good method is to prepare a table showing the impedance of each section of line and also of the generators. These figures can then

Fig. 105.—Resistance, Inductance and Impedance of Overhead Lines

Resistance (R)	Inductance X and impedance Z per wire per mile							
Spacing, ft.	2		4		8		15	
Size wire	R	X	Z	X	Z	X	Z	X	Z
25 Cycles								
0000	0.267	0.245	0.365	0.280	0.387	0.315	0.413	0.348	0.437
000	0.336	0.251	0.420	0.286	0.442	0.320	0.463	0.352	0.487
00	0.423	0.257	0.495	0.291	0.563	0.326	0.535	0.358	0.553
0	0.534	0.262	0.595	0.297	0.611	0.332	0.628	0.364	0.647
2	0.849	0.277	0.895	0.312	0.905	0.347	0.917	0.378	0.930
4	1.35	0.288	1.38	0.324	1.39	0.358	1.396	0.390	1.40
6	2.15	.....	.....	.....	.....	.....	.....	0.401	2.19
8	3.400	.....	.....	.....	.....	.....	.....	0.413	3.43
60 Cycles								
0000	0.267	0.587	0.645	0.672	0.723	0.755	0.801	0.831	0.873
000	0.336	0.601	0.690	0.685	0.763	0.769	0.839	0.845	0.908
00	0.423	0.615	0.745	0.699	0.815	0.782	0.888	0.859	0.958
0	0.534	0.629	0.825	0.714	0.892	0.797	0.958	0.873	1.03
2	0.849	0.664	1.075	0.748	1.130	0.832	1.188	0.908	1.23
4	1.35	0.692	1.515	0.776	1.555	0.860	1.60	0.936	1.64
6	2.15	.....	.....	.....	.....	.....	.....	0.964	2.35
8	3.40	.....	.....	.....	.....	.....	.....	0.992	3.54

Above values are to be used with voltage to neutral. Sizes No. 0000 to 0 are stranded: others are solid. Based on 97 per cent conductivity at 20°C. or 67°F. Values in table computed on slide rule.

be combined in any way desired to determine the impedance of a particular path. In obtaining the impedance of several sections of a system, the resistances and inductances must be added separately and the two sums combined geometrically. The inductance varies with the size of the conductors and with the

distance between them, which in the case of a cable is determined by the thickness of the insulation. The characteristics of cable can usually be obtained from the manufacturers. A 15,000-v. No. 0000 cable at 60 cycles has an impedance about 23 per cent greater than its ohmic resistance, whereas, the impedance of a 150,000-v. line having the same size copper conductor spaced 15 ft. apart is about three and one-quarter times the

Fig. 106.—Approximate Ohmic Resistance and Impedance of Three-conductor Cables, at 60 Cycles

Size	Resistance, ohms per mile	Impedance, ohms per mile					
		Working voltage					
		3,000	5,000	7,000	10,000	15,000	20,000
2	0.850	0.858	0.859	0.863	0.867	0.872	0.884
1	0.674	0.692	0.696	0.700	0.706	0.712	0.724
0	0.535	0.545	0.547	0.552	0.558	0.565	0.580
00	0.424	0.436	0.439	0.444	0.452	0.460	0.478
000	0.336	0.352	0.352	0.357	0.365	0.374	0.396
0000	0.267	0.280	0.283	0.288	0.296	0.306	0.332
250000	0.227	0.245	0.245	0.252	0.261	0.272	0.299
300000	0.188	0.210	0.210	0.217	0.227	0.241	0.270
350000	0.161	0.187	0.187	0.194	0.204	0.217	0.250
400000	0.141	0.166	0.166	0.174	0.185	0.199	0.234
450000	0.127	0.148	0.148	0.156	0.167	0.182	0.221
500000	0.113	0.137	0.137	0.144	0.156	0.172	0.212

Based on Pure Copper, 75°F. with an allowance of 3 per cent for spiral path of conductors, 60 cycles per second and standard thickness of varnished cambric insulation. Values are practically the same for other types of insulation. These figures are also approximately correct for 98 per cent conductivity copper at 65°F.

value of its resistance. The resistance, inductance and impedance of aerial transmission lines having various wire spacing are given in Fig. 105, and Fig. 106, which shows the resistance and impedance of various kinds of three-conductor cable.

The method of computing the impedance of a circuit, including a line, generator and transformer, is shown in the following example:

Assume.—A 5,000-kva., 60-cycle generator having 10 per cent reactance drop.

A 5,000-kva. bank of transformers having 1 per cent resistance drop and 5 per cent reactance drop.

50 miles 45,000-v. line No. 0 copper conductors spaced 4 ft. apart.

All values of resistance, reactance and impedance will be reduced to terms of 45,000 v.

Full-load current $= \dfrac{5,000,000}{\sqrt{3 \times 45,000}} = 64$ amp.

Star voltage $= 26,100$.

Generator Characteristics:

Reactance drop $= 10$ per cent of $26,100 = 2,610$ v.

Reactance $= \dfrac{2,610}{64} = 41$ ohms.

Transformer Characteristics:

Resistance drop $= 1$ per cent of $26,100 = 261$ v.

Resistance $= \dfrac{261}{64} = 4.1$ ohms.

Reactance drop $= 5$ per cent of $26,100 = 1,305$ v.

Reactance $= \dfrac{1,305}{64} = 20$ ohms.

Line Characteristics (from Table, Fig. 105):

$R = 50 \times 0.534 = 26.7 \qquad X = 50 \times 0.714 = 35.7$

Summary:

	R	X
Generator..................	Negligible	41.0
Transformer...............	4.1	20.0
Line......................	26.7	35.7
Total.................	30.8	96.7 ohms.

$$R^2 = 950$$
$$X^2 = 9,150$$
$$Z^2 = R^2 + X^2 = \overline{10,100} \qquad \text{Hence } Z = 100.5 \text{ ohms}$$

The short-circuit current is therefore $\dfrac{26,100}{100.5} = 260$ amp. for the first instant. As shown in Fig. 94, tne initial current will decrease until the sustained value is reached. In this example the sustained value is probably about twice full-load current, or say 130 amp. If the lines should have more impedance, or if less generating capacity should be connected to the busbars, the generator reaction would have less effect

in cutting down the current, and the calculated results would need less correction.

Alternator and Transformer Constants.—The characteristics of alternators vary through a wide range, but it is usually assumed that their reactance is about 8 per cent, which allows a maximum instantaneous root-mean-square asymmetrical short-circuit current of 19 times full load. The maximum sustained short-circuit current is usually assumed to be between two and one-half and three times full load, although some machines, particularly turbo-alternators, are now being built which have a sustained short-circuit current of about one and one-half times full load. It is usually safe to assume that a transformer has 1 per cent resistance drop and from 3 to 4 per cent reactance drop.

Effect of Low Voltage.—The most important requirement of a power-directional relay is that it will operate when the potential at its terminals is between 1 and 2 per cent of normal. If we assume the case of a No. 0000 cable normally carrying 300 amp. at 12,000 v., connected to a generating station having a short-circuit current of 3,000 amp., the loss which would occur between the busbars and a metallic short-circuit 100 ft. from them would be 45 kw. per phase, or less than three-quarters of 1 per cent of the relay setting. This shows the absurdity of installing relays which require a percentage reversal of 5 or 10 per cent to operate them.

The statement has frequently been made that a power-directional relay cannot operate when there is no voltage, but neither can there be a flow or current unless there is a difference of potential. The problem is therefore nothing more than a question of securing a contact-making wattmeter which is sensitive enough to operate on the small potential that is always present when a short-circuit occurs. Numerous tests have been made which show that when a cable breaks down the arc through the insulating space between conductors will maintain a voltage of between 1 and 2 per cent, and it has been found that a higher voltage is maintained when the current is small than when it is excessive, a fact which materially assists power-directional relays. It should be pointed out that on large systems it is practically impossible to obtain a metallic

short-circuit because any small object that could be brought into contact with the busbars would be immediately destroyed. The only possibility for obtaining a short-circuit that will lower the voltage to a point where reverse-power relays cannot operate is the case of an extra-high-voltage system where the short-circuit current is so small that it cannot burn off a metallic connection. For instance, on a 150,000-v. system of some magnitude, the current at short-circuit may not exceed 500 amp., which could be carried for some seconds by a telephone wire dropped across a transmission line. The possibility of interruption from this cause is remote, because a short-circuit across three wires will not often occur, and when only two wires are involved the low-voltage condition does not exist except on one phase.

Effect of Unbalanced Short-circuits.—In the past the operation of power-directional relays has been somewhat unsatisfactory, because means were not taken to insure correct operation at times when the power-factor of the system was bad, due to unbalanced short-circuits. As a result of several years' investigation, it has been found the the methods of connecting reverse-power relays with their potential coils in star, as has been the usual custom, is theoretically incorrect, and the relays may fail to operate upon the occurrence of the most common form of short-circuit. When unbalanced short-circuits occur, a large number of combinations of circumstamces are possible, but it has been found that the most severe condition is when only two conductors of a three-phase line are short-circuited, and if relays will operate properly under this condition they will satisfy practically all the others.

In Figs. 107a and 107b are shown, in a rather incomplete way, the vector relations on a simple electric circuit when a short-circuit occurs between the wires B and C. Figure 107b shows at a the voltage triangle at the generating station and at b the voltage triangle some distance from the generating station. At c is represented the conditions at the short-circuit, and it will be seen that the long sides of the voltage triangle have closed in together. It will also be observed that the two-star voltages, OB and OC, are in phase. Referring again to a, if the circuit has no inductance, the current which flows into

the short-circuit will be in phase with the voltage BC, as is shown by the vectors IB and IC. If such a condition were possible, none of the relays at the short-circuit could operate, because the power factor is zero. Since, however, there is always induc- tance in the circuit, the current will lag somewhat, as shown by the vectors I^1B and I^1C. The result of this is to cause one of the relays at the short-circuit to operate forwards and the other one to operate backwards. Figure 107b shows the effect of an inductive load on the system. The short-circuit currents are represented by dash vectors, and the resultant of the short- circuit currents and load currents by heavy vectors. The

FIG. 107a.   FIG. 107b.

FIG. 107a.—Vector diagram of current and voltage with short circuit when load is non-inductive.

FIG. 107b.—Showing the vectors with inductive load.

general result of the load current on the system is to make less pronounced the effect due to the short-circuit, as will be observed upon comparing b in Figs. 107a and b. In the former case, one of the relays operates backwards, but in the latter case, both of them read properly.

In the above explanation, the condition in only one line has been shown, and the question might immediately arise as to what difference it makes whether or not one relay operates backwards, so long as one of them operates to trip the circuit breaker. The answer is that the same condition exists in all the good sections of line parallel to the trouble, with the result that their circuit breakers will also be opened. This difficulty can easily be overcome by using the delta-delta connection of voltage transformers as explained under "Instrument Trans- formers and Groupings." With this connection, the current in each relay leads the voltage in each relay by 30 deg. when the line power factor is 100 per cent instead of the relay current and voltage being in phase at 100 per cent line power factor.

Then even though the line power factor should drop to almost zero during a short-circuit, the current in any relay could not lag more than 60 deg. behind its voltage.

CHARACTERISTICS OF RELAYS

From the foregoing discussion, it will readily be seen that the relays must be absolutely reliable and dependable and have as well a high accuracy both initially and maintained. Relays for the protection of overloads, or rather excess currents, should have two distinct adjustments: time and current. The time setting is of course easily set according to the relay curves to obtain the desired delay.

Much misunderstanding has prevailed in the past regarding the current adjustment. In the case of straight-overload relays, the relay is easily selected and set according to the magnitude of the load and the overload. But on differential protection, however, many relays have been used with very low-current windings in order to make them susceptible to slight unbalancings in current. The result is that they were too sensitive and tripped the breaker on slight surges due to throwing the apparatus on the line, or line switching or synchronizing. Attempts were made to give these relays a time delay with only slightly better results. In such case, a relay should be used with a comparatively high overload setting and the time adjusted to instantaneous.

On the power-directional relays, there should be three distinct adjustments: time, current, and direction. The time and current adjustments should be set same as the current relay, while the directional adjustment must be so sensitive that it will function on a very small reversal of power flow even though the potential drop to 1 or 2 per cent of normal.

Much confusion has existed regarding the correct use of the power-directional and the watt relays. For instance, consider a plant supplying part of its own power and buying the rest from a nearby station with provisions to limit the power flow. Neither a power-directional nor a watt relay alone will give the desired results; both must be used.

When considering the adjustment of the power-directional relay, it must be remembered that it is for protection alone,

and so the current setting must be high enough so that it can never trip no matter how high the current may be under normal load on the system in either direction. If the normal load current produces a maximum of 3 amp. in the secondary of the transformer, then the relay should be set for a minimum of about 4 amp. In many cases, it has been found desirable to set these relays as high as 10 to 12 amp.

The time limit required is determined solely by its relations to the time delays of the other relays on the system. Usually the time limit is set rather low as the power-directional relay is usually placed at the most critical point on the system and is expected to operate first in case of trouble. Sometimes they are even set to operate instantaneously, but this should be done with great care as the breakers may be popping out upon the occurrence of the least surge due to switching or synchronizing.

As previously stated, the time limit is practically independent of the current setting of the relay so that in cases where instantaneous action is desired, nothing is gained by making the current setting small.

In order that it may operate under the most severe short-circuit conditions where the voltage is low, the directional element should be made very sensitive. Consequently small surges on the system may frequently cause the contacts of the directional element to be closed, but this is a matter of no importance because these contacts are also in series with the contacts on the excess-current element, which latter contacts cannot be closed unless there is trouble on the system with a consequent excessive current. Now if the excess-current element of this relay should be set to operate at a very low-current value, say 1 amp., and the load current is 3 amp. these contacts will be closed continuously. This not only destroys the time-limit feature of the relay, but places the service at the mercy of the sensitive directional element, which is likely to operate whenever a heavy surge occurs on the system, even if this surge is a matter of no importance to the service.

One of the places where a relay with a low-current winding has been used is on city distribution systems which have their own stand-by steam plant, but which purchase part of their

power from a high-voltage hydro-electric system. It is obvious that the small steam plant cannot hold up the electric system during troubles which are inherent in the electric system and which occur altogether too frequently. Nevertheless, even if the receiving system should have sufficient steam turbine capacity constantly floating on the line to pick up the electric load the instant it is lost, such a change cannot be made without considerable disturbance and there is always a possibility that the steam plant will be unable to pick up the load as quickly as is necessary in order to save the service. Now there can be only two conditions existing at the steam plant, either there is sufficient steam-generating capacity connected to the busbars so that the load can be picked up instantly, and if this is the case there is sufficient capacity available to operate reverse-power relays having a normal-current setting; or else there is insufficient steam capacity to pick up the load, in which case it will be desirable to hold on to the electric power through whatever manner of disturbance may occur.

This argument is usually met by the statement that the hydro-electric system frequently "goes under" due to a failure in the water supply or due to short-circuit on the transmission system which cuts off essential plants. Of course, under such circumstances, it is not desirable for the steam plant to attempt to carry all the load of the electric system, and it is reasonable to separate the two, but the power-directional relay cannot be depended upon to make this separation in the proper manner. For this purpose use should be made of a watt relay which is essentially a contact-making wattmeter and which will close its contacts when the power exceeds a predetermined amount in a predetermined direction. This device is much simpler than the power-directional relay and can be depended upon to operate with great accuracy. However, it is not intended to clear short-circuits, and in the installation which we have been considering, it will be necessary to make use of the power-directional relays to take care of line troubles and the watt relay to prevent the steam system from attempting to carry the hydro-electric system. This arrangement will give complete protection, and if the electric system is in itself properly sectionalized so as to take care of its own troubles, there will be very little

necessity for keeping the stand-by steam plant in readiness to instantly carry the entire load. Viewed from this standpoint the question becomes of considerable importance and will justify careful consideration on the part of prospective relay users.

Another important point is that relays with a low-current winding not only have a high impedance but they will not carry a heavy load without severe overheating.

As will be explained later under the pilot-wire systems, low-current relays find a legitimate application when the currents must be transmitted a long distance between the current transformer and relay. In this case, however, use is made of current transformers whose normal secondary current is the same as the current rating of the relay.

CHAPTER X

INSTRUMENT TRANSFORMERS AND GROUPINGS

With the exception of the smaller, low-voltage installations, where the relays may be connected directly to the line and wound to carry the line current, it is essential to connect protective relays to the secondary circuit of instrument transformers. It then becomes necessary to have an accurate knowledge of the performance of an instrument transformer during times of electrical trouble.

Instrument Transformers.—There are two classes of instrument transformers available: the "current" or "series" transformer and the "voltage," "potential" or "shunt" transformer. The current transformers are used to carry the main-line current in their primary and reproduce in their secondary circuit a smaller current which bears a definite relation in phase and magnitude to the primary current. Another very important function of the current transformer is to insulate the secondary circuit, to which are connected the relays, from the high tension of the primary.

Current transformers are required for relays which must function on a predetermined condition of the current in a circuit. The primary is connected directly in series with the line, and several current instruments may be connected to the secondary. Part of the line current acts as the magnetizing current for the transformer iron and for a fixed number of instruments in the secondary; a rise or fall in the line current requires a corresponding rise or fall in the secondary voltage to force the secondary current through the connected instruments. The magnetic flux thus follows the rise and fall of the primary or line currents, until the point of saturation is reached when the ratio breaks down.

In any transformer, the primary ampere-turns may be considered as made up of two parts, one small element which supplies the magnetizing and core-loss current, and another

element which supplies the "working current." The "working current" ampere-turns are always exactly equal to the secondary ampere-turns.

As generally used, the current transformer "steps down" from a large current to a small one, so that the primary winding consists usually of few turns and the secondary of many turns.

Inherent Errors.—If the exciting current could be reduced to zero, the secondary ampere-turns would equal the primary ampere-turns and would be exactly in phase opposition. The transformer would then produce a current in the meters which would, under all conditions, be proportional to the line current and in exact phase opposition to it. It will be noted, however, that there is a ratio error and also a phase displacement. The losses in the core are the disturbing elements which cause both of these inherent errors. For that reason the cores of current transformers should be made of generous proportions and of the best magnetic material, so that the density of the magnetic flux and the resulting loss-elements will be kept as low as possible.

Ratio Error.—If the exciting current decreased exactly in proportion to a decrease in the primary current, the per cent ratio error and the correction factor would be constant for all primary currents. However, it will readily be seen that at a flux density corresponding to one-half normal primary current, the exciting current is more than one-half of its value at full primary current, and that the exciting current therefore forms a disturbing element of relatively large proportions as the primary current decreases.

On some types of current transformers, especially the "hole" or "through" type, the ratio breaks down badly on excessive overloads. This is made worse by the fact that several instruments may be connected to the secondary. For this reason many systems make a practice of supplying two sets of transformers: one for the metering equipment and one for the protective equipment.

As an example of how the ratio breaks down, consider the curve in Fig. 108. This shows that with a secondary load of 40 v. amp., should the short-circuit current be 20 times normal, the secondary load on the transformer would increase from

8

40 v. amp. to 16,000 v. amp. and this in many cases is above the saturating point of the transformer. This necessitates an accurate knowledge of the ratio of the transformer with various secondary loads and various primary currents in order to enable the relays to be set accurately.
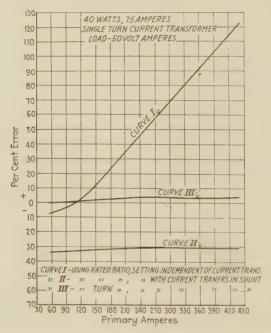
Fig. 108.—Curve showing how the ratio of a series transformer breaks down on heavy overload.

Magnetization of Core.—The magnetic history of the iron also affects its losses. If the core has been magnetized, either by passing direct current through the coil, by opening the secondary circuit with a load on the primary, or by a heavy overload on the primary, the iron loss and magnetizing current will be abnormally high and the ratio and phase-angle errors will be slightly greater than normal. Such a transformer can be demagnetized and restored to normal condition by passing about 150 per cent of normal current through the primary, with the secondary connected to a resistance of 20 to 30 ohms and grad-

ually reducing the resistance to zero. Great care should be taken not to come in contact with the secondary leads during this operation as dangerous voltage may be induced.

Effect of Secondary Load.—The instruments connected in the secondary circuit of the transformer are placed in series, so that the secondary current will pass through each. As instruments are added, higher voltage is required to force the current through them. This requires higher magnetic density in the iron, which increases both the iron loss and the magnetizing current, hence both the ratio and the phase-angle errors are magnified. For the sake of accuracy, therefore, there is a limit to the number of instruments that should be placed on a single-current transformer.

The ordinary measuring instruments are not non-inductive. The power factor of the load of instruments varies with the different combinations used. In general, and within the limits of the usual groups of meters, it may be said that for the same volt-ampere load, the greater the inductive element in the load, the less will be the phase displacement error and the greater the ratio error. While the variations in the errors are not enough to affect the accuracy to a great extent, the power factor of the load must be recognized in preparing performance curves of current transformers.

For a given instrument load on the transformer, the secondary ampere-turns bear a definite relation to the primary ampere-turns, for each value of the primary-load current. Therefore, by properly proportioning the number of turns in the windings, it is possible to raise the secondary current to overcome the ratio error. However, owing to the inherent variation of the ratio error, this compensation will not be exactly correct for other values of the primary current.

A current transformer is usually compensated to give, as closely as possible, the correct ratio at 65 per cent of its rated current. As meters and transformers should be selected with a rating 50 per cent greater than the normal current of the circuit, to allow for peaks and overloads, the full-load current of the circuit represents about 65 per cent of the current rating of the transformer and meter. Therefore, the greatest accu-

racy of meter readings is attained with full-load current in the circuit.

Higher frequencies produce lower magnetizing current and lower iron loss, and therefore result in lower percentage of ratio error and smaller phase angle. The variations are small, however, and most current transformers may be used at any frequency from 25 to 133 cycles.

As the operation of the current transformer depends on current only, variation of line voltage has no effect on accuracy. A type of current transformer must be chosen, however, having insulation suitable for the voltage of the line on which it is to be used.

The shape of the primary-current wave affects, to a certain extent, the maximum induction and therefore the iron losses, and also affects the shape of the secondary-current wave, which may introduce slight errors in some meters. These effects are, however, negligible.

Rise of temperature increases the resistance drop in the windings, which necessitates an increase in the secondary voltage. This, in turn, necessitates an increase in the magnetic density required in the iron and thus affects the accuracy. The resistance drop is, however, only a small part of the induced voltage, and the temperature rise of transformers should be within the A. I. E. E. limit of 55°C. The variations of accuracy due to temperature rise are very slight.

A current transformer, to be accurate, requires at least 600 ampere-turns (based on normal primary current). In the "through-type" there is only one primary turn, so that this type cannot be made for normal currents of less that 600 amp. without sacrificing accuracy. In cases where accuracy is required over only a limited range, as for relays or trip coils, the use of this type is entirely satisfactory for normal current as low as 100 amp. Where it is possible to calibrate the instrument with the transformer, it is entirely satisfactory to use this type of transformer.

The momentary current due to a heavy short-circuit on a large system is extremely great and the mechanical stresses set up between the primary and secondary windings of a current transformer due to this current are very large. In the "through-

type" of transformer, these stresses are balanced within the transformer itself. This is a good type, therefore, to apply where there is a liability of short-circuits.

The objection has been put forward that the accuracy of the "through-type" of transformer is affected by the position of the primary conductor in the transformer opening. This would be true to a slight extent if the conductor were very small in proportion to the transformer opening. In practice it amounts to a laboratory refinement which is of no commercial importance.

FIG. 109.   FIG. 110.

FIG. 109.—Connections of three-wire transformer on single-phase three-wire circuit.

FIG. 110.—Connections of two transformers on single-phase three-wire circuit.

Single-phase Groupings.—For single-phase circuits a transformer is required for each circuit to be protected. In the case of three-wire circuits, either two ordinary transformers or one three-wire transformer may be used, connected as shown in Fig. 109 and Fig. 110. The three-wire transformer is so connected that the secondary carries current proportional to the average of the currents in the outside wires of the circuit. When two single transformers are used, connected like Fig. 110, the current in the relay circuit is the sum of the two secondary currents. To use standard apparatus throughout it would be necessary to use transformers of double the actual ratio required so that the sum of the secondary currents would not exceed the 5 amp. for which the relay coil is designed. Such transformers would then be operating at one-half their normal primary current, and their accuracy would accordingly suffer somewhat.

Two-phase Groupings.—Figure 111 shows a number of possible groupings of current transformers on various two-phase circuits, with the corresponding vector diagrams. Assum-

(a)
(a) Three-wire. One transformer in each phase. V-connection.
(b) Three-wire. Transformers in one-phase and common wire. V-Connection.

(c)
(c). Four-wire, independent. One transformer in each phase. V-Connection.
(d) Four-wire, inter-connected. T-Connection.
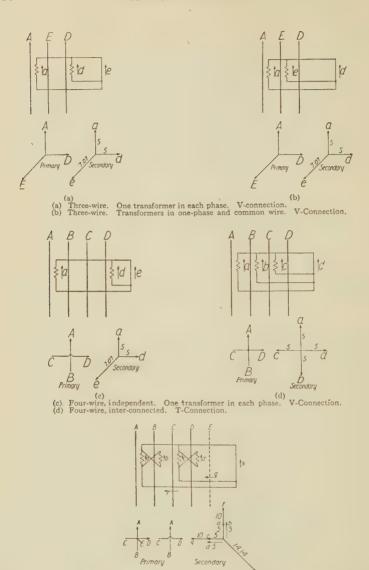
Fig. 111.—Two-phase groupings of current transformers showing connections and vectors.

ing that the transformers have standard 5-amp. secondary
windings, the numbers on the vector diagrams show the currents
in the corresponding branches of the circuits. The preferable
arrangement for any case depends on the type of instrument
to be energized. For ammeters, a reading in each phase usually
is all that is necessary, while protective relays should be so
connected that trouble on any line will be detected.

NECESSITY FOR THREE TRANSFORMERS ON THREE-PHASE CIRCUITS

That the use of two transformers and two relays for the pro-
tection of a three-phase circuit is not sufficient is apparent from
Fig. 112, which shows the relays at *A* and *B* with the transformers
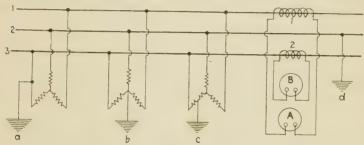
Fig. 112.—Showing why two series transformers are not sufficient for three-phase protection.

at 1 and 2. If a ground should occur on line 2, and another
ground on a generator winding or lead as at *a* or *b* or *c*, then

Fig. 113.   Fig. 114.
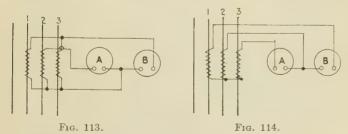
Fig. 113.—Wrong connection of three transformers and two relays.
Fig. 114.—Another wrong connection.

there would be a heavy short-circuit current which would
flow through the middle line without passing through either
relay.

Three transformers cannot be used with two relays with the connections as shown in Fig. 113 as it will be noted that in the event of a short between lines 1 and 3, there will be no excess current in the relay. In Fig. 114, a short due to ground on either lines 1 or 3 will tend to force the excess current through the middle transformer, thereby piling up the voltage due to the high impedance, so this connection also cannot be used.

FIG. 115.   FIG. 116.
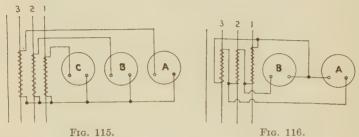
FIG. 115.—Proper connection for three relays and three transformers.
FIG. 116.—Delta connection to two relays.

The best combination is three transformers with three relays as in Fig. 115 as this enables each relay to receive the full current from its respective transformer. This is the most used connection. Two relays may be connected to three transformers with the delta connection as in Fig. 116 or with the Z connection as in Fig. 117.
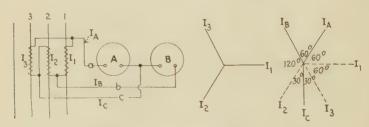
FIG. 117.—Z-connection to two relays.

Advantages of the Z-Connection.—Assuming that the normal current in the transformer secondary is 5 amp., then with the delta connection, the normal current in the relays is 8.66 amp., thus requiring specially-wound relays. With the Z-connection,

however, the normal-relay current is only 5 amp. In the case of a short between two lines, the currents increase as shown in the table, Fig. 118, showing that both delta and Z give equal pro-

Fig. 118.—Table Showing Increase in Current with Z and Delta Connections. Overload in Two Lines[1]

Trans. current		Relay current		Increase in current		Per cent ratio	
l_1	l_3	Z	Δ	Z	Δ	Z	Δ
5	5	5	8.66	0	0.0	0	0
6	6	6	10.39	1	1.73	20	20
8	8	8	13.86	3	5.20	60	60
10	10	10	17.32	5	8.66	100	100

[1] Alfred J. A. Peterson in the *Electric Journal*.

Fig. 119.—Table Showing Increases in Current with Z and Delta Connections. Overload in One Line Only[1]

Trans. currents		Relay currents		Increase in current		Per cent increase		Per cent ratio	
i_1	i_3	Z	Δ	Z	Δ	Z	Δ	Z	Δ
5	5	5.00	8.66	0.00	0.00	. . .	. . . . .	100.0	173
6	5	5.57	9.54	0.57	0.88	11	10.15	92.8	159
7	5	6.25	10.43	1.25	1.77	25	20.4	89.3	149
8	5	7.00	11.35	2.00	2.69	40	31.0	87.5	142
9	5	7.82	12.30	2.82	3.64	56	42.0	86.9	137
10	5	8.66	13.23	3.66	4.57	73	53.0	86.6	132
12	5	10.43	15.13	5.43	6.47	109	75.0	86.9	126
15	5	13.23	18.04	8.23	10.38	165	120.0	88.2	120
20	5	18.04	22.94	13.04	14.28	361	165.0	90.2	115

[1] Alfred J. A. Peterson in the *Electric Journal*.

tection. But in the case of a three-phase four-wire system or a grounded neutral system, a short-circuit to neutral or ground will cause the currents to increase as in table, Fig. 119, thus showing that the Z-connection gives much better protection.

When making the Z connection, the following rule should be employed: Connect two positive transformer terminals to the first-relay terminal. The negative terminals of the first and third transformer go to the second-relay terminal and the remaining positive and negative transformer terminals go to the common between the two relays. Thus referring

Fig. 120.—Various Z Combinations

LINE	Relay A	Relay B	Relay C
	1–3	4–5	2–6
	1–3	3–6	2–4
CURRENT	1–2	4–6	3–5
TRANS.	1–2	5–6	3–4
	2–3	4–6	1–5
LOAD	2–3	4–5	1–6

to Fig. 120 it will be seen that there are six combinations which produce the same results. Figure 121 gives the various groupings and vector diagrams.

Opening of Secondary.—The secondary circuit of a current transformer should never be opened while the primary is carrying current. If it is necessary to disconnect instruments the secondary should first be short-circuited. If the secondary circuit is opened, a difference of potential is developed between terminals which is dangerous to anyone coming in contact with the meters or leads. The cause of this high voltage is that with open secondary circuit all of the primary ampere-turns are effective in producing flux in the core, whereas normally but a very small portion of the total perform this function. The danger is magnified by the fact that the wave form of this secondary voltage is peaked, producing a high-maximum value. A high flux produced in this way may also permanently change the magnetic condition of the core so that the accuracy of the transformer will be impaired.

Voltage Transformers.—Voltage transformers (also called potential or shunt transformers) are used to insulate the relay circuit from the high-tension line circuit, and to reproduce a voltage on the relays which is in direct proportion to the line voltage.
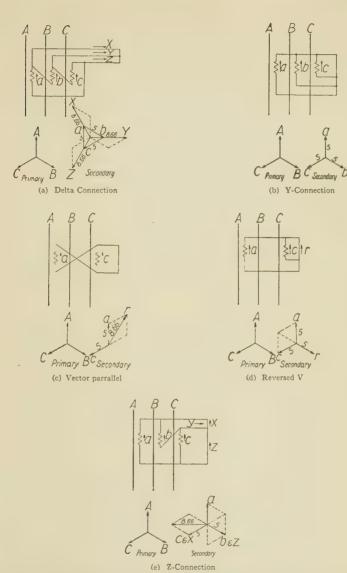
Fig. 121.—Three-phase groupings of current transformers showing connections and vectors.

This transformer is in principle of operation an ordinary constant-potential transformer specially designed for close regulation, so that the secondary voltage under any conditions will be as nearly as possible a fixed percentage of the primary voltage.

The only thing which can affect the accuracy of a voltage transformer, without entirely destroying it, is a change in the iron which would change the exciting current. Inasmuch as the effect of the exciting current is small, and modern transformer iron is non-aging, it is safe to assume that the original calibration of a first-class modern transformer is permanent.

Voltage transformers are compensated for their iron losses at their rated voltage. When used on some other voltage, either higher or lower, an error is introduced. In general, this error will not be more than 0.15 per cent when the applied voltage is from 50 per cent to 110 per cent of rated voltage. A voltage transformer should never be used on a circuit whose voltage is more than 10 per cent above the rated voltage of the transformer.

Ordinary frequency variation and wave shape also affect the iron losses, but their effects on the accuracy of the transformer cannot be detected.

As the operation of the voltage transformer depends only on the voltage applied at its terminals, variations in the line current have no effect whatever on its accuracy.

As voltage transformers are designed for close regulation, they should have a temperature rise well within the A. I. E. E. limit of 55°C.

Polyphase Groupings.—In general, two voltage transformers are sufficient for any two-phase or three-phase circuit. Figures 122 and 123 show various groupings of transformers on two-phase and three-phase circuits respectively. The numbers shown on the vector diagrams of secondary connections show the voltage between the points indicated, in percentage of the voltage between lines (corrected for ratio of the transformers). In case a different secondary voltage between these points is desired, transformers of suitable ratio should be selected. The highest accuracy is attained with standard transformers when the secondary voltage of the transformers is 100 v., but

in some cases 58 v. is required to produce proper registration of the relays.

It should be noted that the *V*-primary to *V*-secondary connection (*b*), Fig. 123, produces the same results as the "delta-delta" connection (*a*) and saves one transformer. The "delta-delta" connection is therefore seldom used commercially. The *V-V*
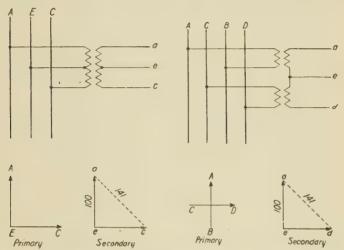
FIG. 122.—Two-phase groupings of voltage transformers showing connections and vectors.

connection under some conditions produces slightly higher error, but the difference is not considered of sufficient importance to warrant the expense of the extra transformer.

To check the correctness of the connections of voltage transformers on three-phase lines, three voltage readings are necessary. These three voltage readings should bear the relations shown in the diagram.

The secondary terminals of a voltage transformer should never be short-circuited. If they should become short-circuited, a heavy current will flow which, if continued, will burn out the windings.

It is practically impossible to protect thoroughly a voltage transformer with fuses, for the reason that any fuse wire small enough and long enough to open the transformer circuit with certainty during an overload would be mechanically too frail
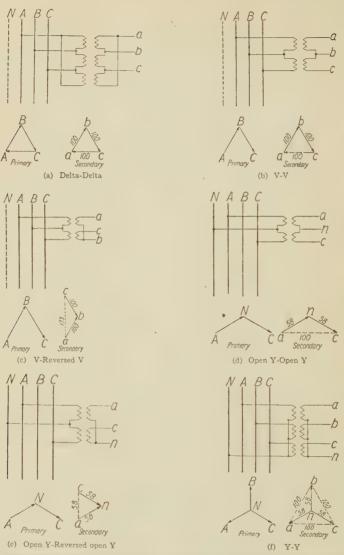
FIG. 123.—Three-phase groupings of voltage transformers showing connections and vectors.

to be handled. Some companies have adopted the practice of connecting the voltage transformers directly to the lines without fuses. This is dangerous, because a short-circuit within the transformer might cause a high-voltage lead to burn off and fall in such a way as to short-circuit the system. To prevent this the larger American electrical manufacturers recommend the use of resistors and fuses in the high-voltage leads of voltage transformers. The resistors limit the short-circuit current to 20 to 40 amp., while the fuses are designed to open such a current.

In normal operation, the resistors carry only the very small primary current of the voltage transformer, and the drop in voltage which they cause is inappreciable.

Load on Transformers.—If several instruments are connected to the same transformer, the combined load may be found as follows: Let W_1, W_2, W_3, etc. be the true watts required by the several instruments.

And M_1, M_2, M_3, etc. be the magnetizing reactive volt-amperes required by the several instruments.

Then the volt-ampere load on the secondary of the transformer will be

$$L = \sqrt{(W_1 + W_2 + W_3 + \dots)^2 + (M_1 + M_2 + M_3 + \dots)^2}$$

and the power factor of this secondary will be

$$PF = \frac{W_1 + W_2 + W_3 + \dots}{L}$$

These relations are true in single-phase or two-phase systems where the current from each transformer flows through its own load. As an approximation which is fairly close, the volt-amperes of the secondary load may be taken as the sum of the volt-amperes of the several instruments. And the power factor of the secondary load may be taken as the sum of the watts divided by the sum of the volt-amperes.

Three-phase circuits having a set of transformers for each phase are approximately equivalent to three single-phase circuits, and the transformer error, calculated as for a single-phase system, will be the average error. But when only two transformers are used on a three-phase system, the calculation

of the loads on the individual transformers becomes more complicated and is not included here. When accuracy is required such that exact correction for phase-angle and ratio is necessary, two transformers should not be used on three-phase systems.

RELAYS REQUIRING BOTH CURRENT AND POTENTIAL TRANSFORMERS

On single-phase and two-phase circuits, current and potential transformers may be connected to the relays according to the foregoing directions. But when relays requiring both current and potential are used on three-phase circuits, then special provision must be made to maintain the correct phase relations, or rather the phase relations demanded to give adequate protection.

For ordinary watt protection, the relays must be connected so that they always give positive deflection with the load in a given direction. This excludes the connection usually used with two single-phase wattmeters on three-phase. As is well known, the voltage and current on one instrument falls 90 deg. out of phase at 50 per cent line-power factor and the deflection actually reverses below this value. The correct connections are shown in Fig. 124.

With directional relays which are used to sectionalize and isolate a short-circuited line, it was once customary to use the star connection for current transformers and the star-delta connection for voltage transformers as shown in Fig. 125.

This caused the relay current and voltage to be in phase at 100 per cent line-power factor. This scheme is still used, particularly on underground cable systems, where the resistance is high compared to the inductance. But on long, overhead lines and in every case where feeder reactors are used, a short-circuit may be of such low power factor that there will not be enough energy to cause the directional relays to function.

One method of curing this trouble is very simple: The relays should be connected with the voltage coils across the same conductors which are causing the short-circuit. In other words, the voltage coils should be connected in delta in accordance with Fig. 126. Because the current will lag behind

the voltage when a short-circuit occurs, the connection should be so made that at unity power factor the current in the current coils of the relays will lead the voltage by 30 deg. This con-
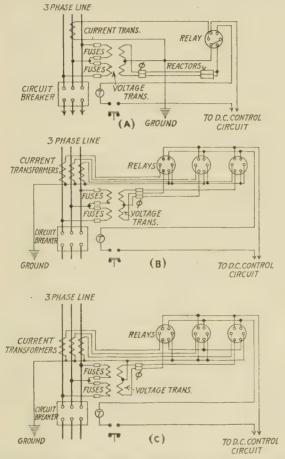
FIG. 124.—Connections for watt relays as recommended by Westinghouse Co.

nection not only overcomes the trouble from distortion, but it allows the relays at all times to operate under a higher power factor.

There are two very simple methods of determining the correct connection. One is to connect the current coils of a single-

9

phase power-factor meter in series with the relay-current circuit, and then with 100 per cent power factor on the line, select the
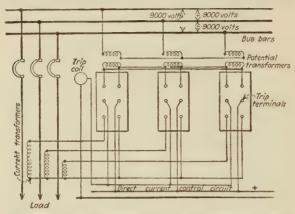
Fig. 125.—Star-delta relay connection, in which the current is in phase with the voltage at 100 per cent line power factor.
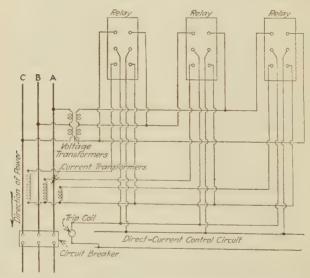
Fig. 126. Connections of relays to cause the current to lead the voltage on non-inductive loads.

pair of voltage leads which give about 86 per cent power-factor lead on the meter.

The second method is to use a single-phase, indicating watt-meter, and with a lagging power factor on the line between 50 and 100 per cent select the pair of voltage leads which give the highest reading.

Just after making the above test is the proper time to see that the contacts are held open.   If they close, the voltage leads must be reversed.

The above discussion is not based solely upon the mathematical study of the problem, but is the result of actual tests made on a number of transmission lines where the reverse-energy relays connected according to the old method have not given satisfactory service.   Experiments have shown that this method of connection should also be used on systems having a grounded neutral.   This connection (with the current 30 deg. ahead of the voltage) must be used with care on an ungrounded neutral system having a heavy charging current to ground.   Difficulty may also be encountered on some systems where the load current is leading.   But in both these cases the short-circuit currents will be much greater than any possible leading current and no difficulty due to incorrect operation of the reverse-power relays will be experienced if the excess-current elements are adjusted to operate only on short-circuits.

Determining Phase Rotation.—In order to function correctly, the directional relays must have the current lead 30 deg. and not lag 30 deg., and in order to obtain this condition it is necessary to determine the phase rotation.   This cannot be determined from an ordinary inspection of the three wires, but is easily determined by small patented devices now on the market or by a simple apparatus consisting of two ordinary incandescent lamps and a suitable reactor connected in Y.   The reactor should have about the same reactance as the lamps have resistance.

Calling the three-phase voltage wires A, B, and C, connect one lamp to A and the other to C, and connect the reactor to B.   One lamp will now burn bright and one dim and the rule is that the bright light always leads the inductance.   For instance, if the lamp connected to A should be bright, the phase rotation is A B C, while if the lamp connected to C should be bright, then the phase rotation would be C B A.

PROTECTION OF MOTORS, TRANSFORMERS GENERATORS, AND LINES

In the early days of electric service, protection of motors and transformers was accomplished by ordinary fuses, which disconnected the apparatus automatically when the current became excessive. Even today, fuses cannot be excelled for reliability on heavy overloads. It was soon realized that there were conditions of overload which the fuse did not take care of adequately, and besides, the fuse was not at all accurate or selective in its action and was quite expensive. For this reason the circuit breaker was developed, but, while it was a great improvement, yet it possessed small "reasoning" or "thinking" power; that is, it was very little better than the fuse in its selective action. This led to the use of the protective relay, a small instrument actuated by the currents in the machines or wires and controlling the action of the breaker. The relay is so flexible in its various connections and so accurate and selective in its action that it is often called the "brains" of an electric system.

While the principal use of the protective relay is on large generating systems and long-distance transmission lines, yet it is often applied to motors and transformers and gives protection and uninterrupted service that can be obtained in no other way.

Protection of Motors.—In its simplest application, the relay is arranged to carry a current proportional to the load current, and, upon the occurence of excess current, close a circuit which trips or opens a circuit breaker. Figure 127 shows a relay A connected to the secondary of a series transformer B. The primary is connected to carry the load current of motor C which is protected by breaker D. Normally the relay contacts are open, but should motor C be overloaded or develop a short-

circuit, the excess current operates the relay, closing the contacts, which in turn complete the circuit to the trip coil of the breaker.

The time between the instant of overload and the instant of breaker opening may be set easily by the time lever on the relay, for instance, referring to the curves, Fig. 171, if the transformer delivers 5 amp. at full load, and No. 10 setting 5 amp. tap is used, then on 150 per cent load, it may take 5 or 6 sec. to trip, this being an indefinite part of the curve.
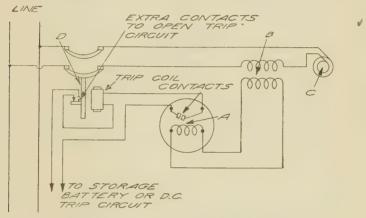
Fig. 127.—Simple overload protection.

On 200 per cent of load (100 per cent overload), it will take 4 sec. to trip. If a shorter time was desired, setting No. 3 might be chosen and the same load would be tripped out in 1 sec. Should the load be over 700 per cent, No. 10 setting would trip out in 2 sec., No. 5 setting in 1 sec. and so on.

Suppose it was desired to have the motor trip on 120 per cent load (20 per cent overload) then the 4-amp. load tap would be chosen. At 120 per cent load the current would be 6 amp. (5 amp. × 120 per cent), but 6 amp. is 150 per cent load on the 4-amp. tap, so the relay would trip out in 6 sec. on No. 10 setting, and quicker on heavier overload and lower settings.

Relays and Transformers Required.—If a two-phase motor is to be protected, two relays and two transformers are necessary, unless an interconnected system is used, when four transformers must be employed. One single, four-pole circuit breaker
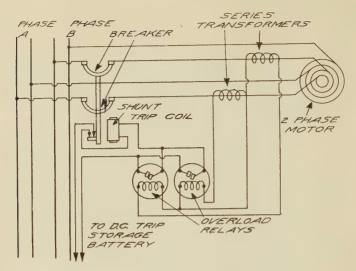
Fig. 128.—Simple protection on two-phase circuit.
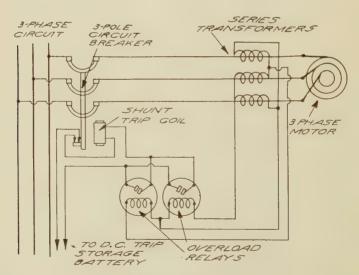
Fig. 129.—Simple overload protection on a three-phase circuit.

would in this case be used and may be operated with one or two trip coils.

Figure 128 shows a two-phase protected motor circuit. If two trip coils were used, they might be connected in parallel,

SINGLE-PHASE WHERE THERE IS NO 3-PHASE GROUNDED NEUTRAL CONNECTED TO SAME

TWO PHASE

TO D.C. TRIPPING COIL.

3-PHASE 3 OR 4 WIRE. THIS GIVES COMPLETE PROTECTION BUT INTRODUCES COMPLICATIONS IN WIRING WHEN RELAYS ARE USED WITH OTHER INSTRUMENTS.

TO D.C. TRIPPING CIRCUIT.

TO D.C. TRIP CIRCUIT. FOR UNGROUNDED NEUTRAL, 3-PHASE CIRCUITS FAILS IN CASE OF GROUND ON B. AND ACCIDENTAL GROUND IN GEN. AT THE SAME TIME

3-PHASE 3-OR 4 WIRE. COMPLETE PROTECTION AVOIDS COMPLICATED WIRING WHEN RELAYS ARE USED WITH OTHER INSTRUMENTS.

TO D.C. CONTROL CIRCUIT

Fig. 130.—Standard connections of Westinghouse induction relays for protecting circuits from overloads. In all cases the trip circuit must be opened by an auxiliary pallet switch on the circuit breaker.

or connected separately to their respective relays. In any case, both phases should be opened.

Three-phase motors may be protected with two relays, but require three transformers for adequate protection, as there

is danger of an overload on any wire should the motor-insulation to ground fail. The reasons for this are discussed under "Instrument Transformers and Groupings." One trip coil is generally used, tripped by either relay, but the breaker must open all three lines. Figure 129 shows the connections.
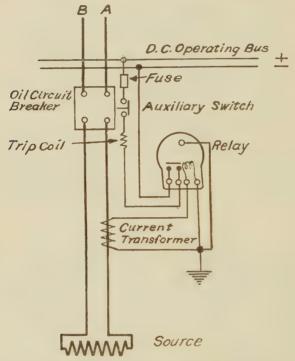
FIG. 131.—Connections of G. E. relay for single-phase circuit protection.

As in the case of the single phase, the time delay in tripping may be easily set by the time lever and load taps on the relay. Figure 130 shows typical diagrams of connections as supplied by the manufacturer. Additional diagrams are shown in Figs. 131 to 135.

Protection of Synchronous Motors.—The problem of protecting a synchronous motor or condenser is peculiar in that it is desirable to have the motor stay on the line just as long as possible in the event of external trouble, and yet it should be quickly disconnected in case of internal trouble. The motor

must be capable of standing heavy overloads for a short time until overheating occurs and yet it must be protected from very severe overloads. Many schemes have been tried with varying success, but about the best protection seems to be obtained by using an overload relay with special time characteristics and
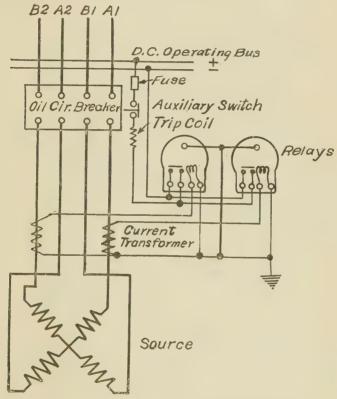
Fig. 132.—Connections of G. E. relay for two-phase protection.

temperature-load relays, which are more fully discussed under "Temperature Relays" in the chapter on "Miscellaneous Relays."

The overload relay employed is similar to those previously described, but it has in addition an instantaneous trip attachment which operates at about 500 per cent of normal load.

This attachment is also provided with a calibrated scale, so that it may be set within wide limits. The relay proper is set for a very long time delay on moderate overloads of 200 to 400 per cent so that a maximum time delay is obtained in mild cases of distress. But should the load exceed 500 per cent then there is no longer time to delay, so the instantaneous trip functions
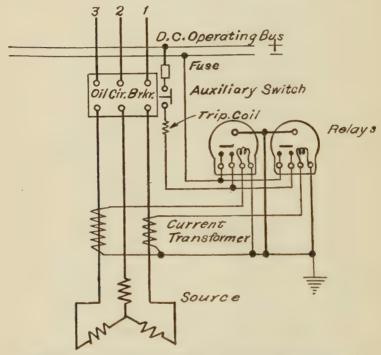
Fig. 133.—Connections of G. E. relays for protection of a three-phase circuit with ungrounded neutral.

and cuts out the motor instantly. This arrangement allows the main-line relays to isolate defective feeders before the synchronous motor is thrown off, but it provides instantaneous protection should a short-circuit develop in the motor or its connecting leads.

Additional protection should be provided for in the form of temperature load relays. This scheme employs exploring temperature coils built right in the stator slots. It allows the machine

to carry a heavy overload until overheating occurs. Even then though the machine be hot, if the load has decreased, the relay will not function; it requires both high temperature and high load to operate it and then it usually warns the operator by means of an alarm or it operates automatic equipment to relieve the load. This relay is more fully described under "Miscellaneous Relays."
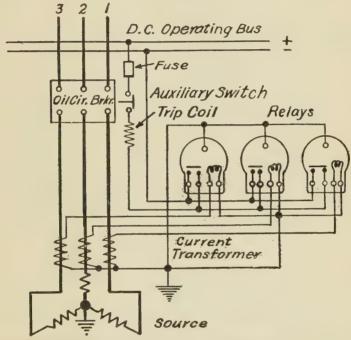
FIG. 134.—Connections of G. E. relays for protection of a three-phase circuit with a grounded neutral.

Protection of Rotary Converters.—Rotary converters should be protected on both A.C. and D.C. side, unless the rotary is operating an isolated line without storage-battery stand-bys or any other chance of the current reversing and motoring the rotary. On the A.C. end, there should be provided the usual current-overload relays to protect against severe overloads. A low-voltage relay should be provided to disconnect the rotary in case of line-voltage failure.

The protection against reversal of current in the D.C. end has been fully described under "Applications of D.C. Power Directional Relays." Every rotary should be provided with an overspeed device of the centrifugal type which provides protection should the other devices not protect it from overspeeding.
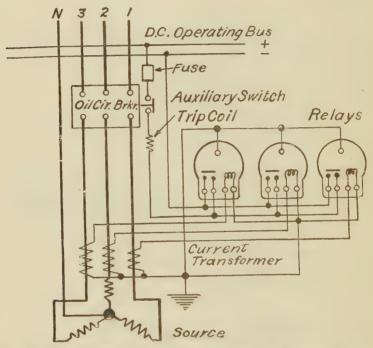
Fig. 135.—Connections of G. E. relays for protection of a three-phase four-wire circuit with or without a grounded neutral.

A complete diagram of the A.C. and D.C. protective relays is shown in Fig. 136.

Transformer Protection.—If the relays are connected on the line side (generating side) of transformers which operate a load of motors, etc., they not only protect the load, but the transformers as well, opening the circuit in case of trouble in the transformers.

But the object is not only to protect but also to preserve

the continuity of service, if possible. So, in important places, instead of using one set of large transformers, two or three sets of smaller transformers are used. For instance, instead of using a 1,200-kva. transformer, three 400-kva. transformers might be used, connected in parallel or "banked." This bank has the same capacity as the big one: but if one set goes bad, the other two in the bank will assume the load, while if the larger
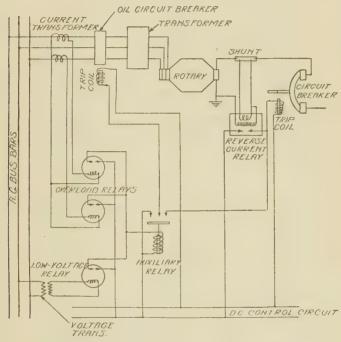
FIG. 136.—Illustrating the use of relays in protecting a rotary converter.

one is damaged, the service is interrupted until repairs or replacement can be made.

It is the function of the relay instantly to locate trouble in a transformer bank and cut out the defective unit without interruption to the load. The elementary principle of differential transformer protection is shown in Fig. 137, where A is a large power transformer having a 10 to 1 voltage ratio, full load current 100 amp. in the primary and 1,000 amp. in

the secondary. Current transformers are chosen for the primary and secondary, which give the same secondary current (generally 5 amp.). These are shown at B and C. The secondaries
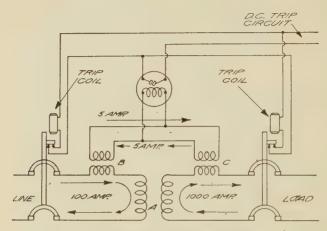
FIG. 137.—Differential transformer protection.
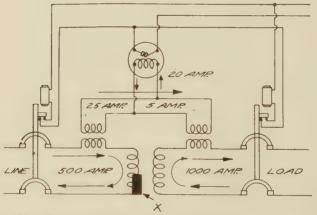
FIG. 138.—Showing currents in relay upon short-circuit in transformer.

are connected in series so that at normal load and correct direction of power flow, a current will circulate in the secondaries and none in the relay, as there is as much tendency for flow in one direction as in the other.

As long as current flows away from the transformer in the same ratio as it flows into it (*i.e.*, 1:10), there can be no current in the relay; but consider Fig. 138. A short-circuit has occurred in the winding at X and a heavy current, say, 500 amp., is flowing into the primary. The secondary current may not drop off much, but the transformer would soon be burned out.
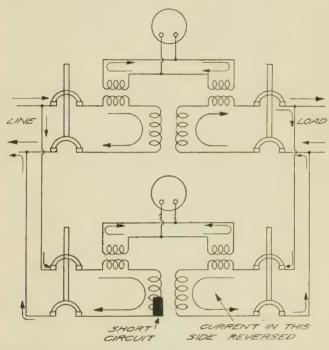
FIG. 139.—Two transformers in parallel; short-circuit in one.

Consider the current in the secondary of the series transformers. Five hundred amperes on a 100 to 5 transformer give 25 amp. on the secondary. The other transformer (1,000 to 5) will allow only 5 amp. to flow through it, so the extra 20 amp. must go somewhere. Consequently, they flow through the relay, close the contacts, and trip both the breakers, effectually isolating the transformer.

Protection in Banks.—If, however, there is another transformer operating in parallel with this and a short-circuit occurs,

the good transformer may feed the bad transformer from the secondary side and cause an actual reversal of power in the defective unit, that is, power feeds into the transformers from both sides as will be seen readily by a consideration of the arrows denoting the direction of instantaneous current flow in Fig. 139.

This shows that the good transformer, as well as the defective one, becomes heavily overloaded and plainly shows that plain overload protection would cut out both transformers in equal time. The differential connections, however, cut out only the defective unit and throw the full load on the other remaining units. Then if the load is too great to be safely carried, the overload relays must necessarily cut out the good unit to prevent it from damage, which results in unavoidable interruption. This would seldom occur; for example, in our previous example of three transformers carrying a load of 1,200 kva., if one goes bad, the others must each carry a load of 600 kva., which is only 50 per cent overload, and should be carried without difficulty. Should two transformers go bad, however, it is obvious that one transformer of 400 kva. could not carry a load of 1,200 kva. and the relays have no alternative but to cut out the last remaining transformer to save it.

POWER-DIRECTIONAL-RELAY PROTECTION

It is quite evident from the foregoing that a power-directional relay may be installed in the load side of the transformer to give adequate protection. Excess-current (overload) relays are installed in the load side as before. Now should an internal short develop in the transformer, the reversal of power in the secondary causes the power-directional relay to trip this side of the transformer, thus relieving the overload on the other transformers in the bank, and then the excess-current relay cuts the transformer out on the line side, thus completely isolating it. In this connection, the excess-current relays give protection against overload in the line or load past the transformer and power-directional relays.

Other Differential Methods.—Special relays, which accomplish the same protection, are sometimes built, in which the actuating winding is wound in two sections. These sections

are connected to their respective current-transformer second-
aries and so arranged that the currents produce a bucking or
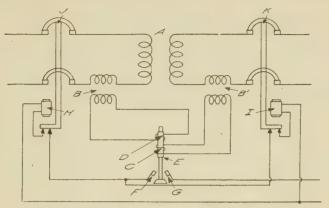
Fig. 140.—Transformer protection by differential relay.
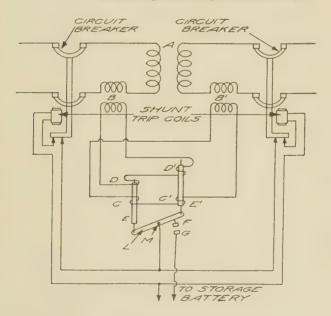
Fig. 141.—Diagram of double plunger relay.

zero flux or magnetism on correct operation. When, however,
the current in one winding exceeds the current in the other,
10

the relay closes the contacts. `Figure 140 shows a plunger-type relay with a double winding, connected for differential protection. *A* is the large power transformer arranged with series transformers *B* and *B'* which supply the relay winding *D* and *C*. Normally these currents oppose each other, producing no effect on the plunger *E*. But should one current reverse, due to a short circuit in *A*, both assist in raising plunger *E*, which closes contacts *F* and *G*, completing the circuit to trip coils *H* and *I* and opening breakers *J* and *K*.
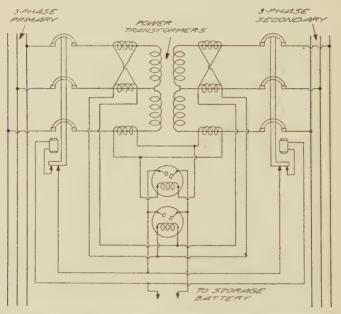
Fig. 142.—Differential protection of two transformers on three-phase circuit.

Another type of relay uses two solenoids operating a pivoted lever which carries the contacts. This is shown diagrammatically in Fig. 141. The two plungers *E* and *E'* work under the influence of the solenoids *DC* and *D' C'*. Normally current from transformer *B'* in winding *D* opposes current from transformer *B'* in winding *C*, resulting in no pull, while current in *D'* assists that in *C'*, resulting in a maximum pull. Should the current in *C* and *C'* reverse, then plunger *E* is pulled up and

plunger E', losing its attraction, falls down. This moves the lever L on its axis M, closing contacts F and G and tripping the breakers.

Polyphase Transformer Protection.—For the sake of clarity, all connections have been shown single-phase. Two-phase requires two duplicates of the single-phase. In three-phase work, the transformers are generally worked in banks of three-phase sets; that is, if one transformer in a set goes bad, the others in that same set go out also, leaving the other sets in the bank to carry the load. Each three-phase set requires only two relays, but requires three series transformers on each side of the transformer.

Figure 142 shows a typical three-phase differential protection connection for a three-phase set.

PROTECTING THREE-PHASE STAR-DELTA BANKS

A three-phase bank of star-delta transformers, having a grounded neutral, attempts to maintain the voltage equal on all phases in case of overload or short-circuit. As a result in the case of a ground on the line, the transformers will supply current to the grounded wire, irrespective of whether these transformers are at substations or generating stations. In other words, if a small bank of transformers is connected to a large system and has its neutral grounded, it will be subjected to a short-circuit every time there is a ground on the system. For this reason, small banks should have their neutrals isolated, not only because of the strain which frequent short-circuits throw on them, but also on account of the frequent interruptions they entail.

The above argument applies principally to high-voltage systems, but it is necessary to consider the same conditions on low-voltage four-wire systems. Four-wire systems are generally used when there is a large amount of single-phase load to be distributed, and as a result the voltage on the three phases is liable to be unbalanced. When a bank of delta-star transformers is connected onto such a system, the question of grounding the neutral must be considered carefully. As a general rule, it is unsafe to make such a ground if the transformers

are small, but if they are comparatively large, it may be advisable to utilize them to assist in maintaining balanced three-phase voltage. This balancing is effected by drawing current from the high-voltage phase and supplying it to the low-voltage phase, with the result that there is a flow of current in the neutral.

The possibility of burning out the transformers can be prevented by installing an overload relay in the neutral and connecting it so that it will sound an alarm or automatically open the neutral.

It frequently happens that star-delta transformers are connected to the main circuit through fuses and trouble is encountered when a single fuse opens. If the transformers are supplying a motor load and the neutral is ungrounded, the motor may run single-phase and damage the motor; on the other hand, if the neutral is grounded, two of the transformers will carry all the load at a much lower power factor than normal. Unless there is a means of indicating a blown fuse, the transformers may carry the overload until burned out. A relay installed in the neutral and arranged to give an alarm seems to be the best means of protection when viewed from the various angles.

Protection of Generators.—Before the advent of thoroughly reliable reverse-power relays, it was considered bad practice to protect the generators by overload relays because they could not be set accurately, and once they started to trip, the current must be reduced very low in order to have them reset. The undesirability of this is realized when the momentary exchange of power between machines, as for instance, in synchronizing, is considered. This rush is not at all serious as it quickly subsides; but if the relay trips the breaker when there is no cause for it, then there is a disadvantage.

The main cause of danger is in a short-circuit occurring in a winding. As this short may be only a few turns, it might quickly burn out a generator unless instantly detected and isolated. If both ends of each winding are accessible this becomes a simple case of protection by the differential method. As shown in Fig. 143 the three windings are connected in Y, with six current transformers as shown.

As in the case of transformer protection, if the same current flows in through one transformer and goes out through the

other, the secondary currents will merely circulate in the windings and will not flow through the relay.

While this will not protect against a short-circuit in any one coil, yet if the neutral begrounded, this arrangement will give complete protection against a ground on any phase or a short-circuit between phases. This is the source of much generator trouble. The burning of a coil itself is usually not serious but it may be accompanied by a burning or welding of the iron laminations, thus necessitating a complete dismantling in order to replace a few sheets of iron.
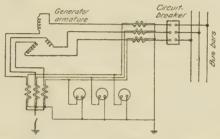
Fig. 143.—Diagram of connections for differential protection of generators using overload relays.

In protection of this sort, the field circuit breaker must also be tripped out as a few short-circuited turns may do great damage if running in an excited field.

As trip connections have been thoroughly discussed previously they are omitted from Fig. 143 for the sake of clarity.

While this method will protect against damage by shorts in the windings or leads, it will not disconnect the generator, no matter how severe the overload. It has the objection that it requires the opening of the neutral point of the generator, which is often difficult, and it cannot be well applied to delta-connected machines. Therefore it is often preferable to protect against generator failure by installing a high-grade power-directional relay.

Protection by Power Directional Relays.—When several alternators run in parallel each one is supposed to take its share of the load, but if the prime mover should fail or the field circuit open, then the alternator may not only refuse

to carry its share of the load, but may become motored. If the refusal to carry load is due to a short-circuit in the winding it may also cause a reversal of power which will intensify the short-circuit. To guard against this, the power-directional (reverse-power or reverse-overload) relays may be installed between the generator and bus. These relays should be set with a time setting of 1 or 2 sec. on the excess-current element as there are often heavy surges of current which may flow between machines due to line switching or synchronizing and a time setting which is too short will cause unnecessary tripping.

Even when the machines are protected in this manner, every generator or prime mover should be provided with an over-speed device which prevents the machines from speeding, as occasions may occur where neither excess-current differential connections nor power-directional relays will give the proper protection against this.

Protection of Single Lines.—While transmission lines are seldom damaged by overloads, except by an arc at one particular point, yet the great majority of disturbances originate on the lines owing to short-circuits caused by the lines themselves falling or becoming grounded, or arcs starting from something shorting the wires, as for instance a crosswire dropping across the lines. Therefore it becomes necessary to disconnect a faulty line very quickly in case of short-circuit. To do this, overload relays are installed in each line to be protected. Even on a single-phase line, two transformers should be employed as a double ground on opposite lines may occur at such points that they cause a short-circuit in which the protective transformer is cut out. The connections are similar to those described for the induction motor in Fig. 130 and need not be duplicated. Additional schemes for line protection are discussed under the pilot-wire and split-conductor systems.

Protection Against Grounds.—If a three-phase line is grounded solid at the neutral, then adequate protection is obtained by the usual line relays. Solid grounding however, has been shown to be undesirable for other reasons in some cases, and therefore the neutral is grounded through a current-limiting resistor. In such cases it becomes necessary to provide additional protection against line grounds, and this is accomplished

by inserting a relay in the neutral connection of the line relays. This relay is then actuated by any unbalanced current which may flow in the neutral.

This relay may be a plain-current relay set to operate on a low value of current as in the case of a system with the neutral grounded through a comparatively low resistor. Or it may be a watt relay used with the connections shown in Fig. 144.
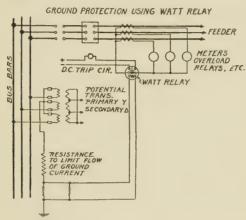
Fig. 144.—Ground protection using a watt relay.

The current coil is inserted in the neutral between the transformers and line relays, while the potential coil is energized by the drop in voltage across a resistor in the neutral of the potential transformers.

This relay is set to operate at a very low value of about 1 amp. or less. It has an adjustable time element and can therefore be set to select between successive sections of line.

PROTECTION OF PARALLEL FEEDERS

When substations are tied into the main generating station or when important industrial concerns are to be supplied with uninterrupted service, reliance is not placed in one single transmission line. Generally there are a number of lines run and connected in parallel. These lines may or may not run on the same poles or the same right-of-way. Then in the event of a crippled line, protective relays are provided to discriminate immediately and isolate the defective line while the other lines instantly assume the increased load without a second's interruption. The following report, taken from the *Thirty-fifth Annual Convention Proceedings* of the A. I. E. E., shows the vast saving which may be expected from the use of properly protected parallel feeders:

SAVINGS EFFECTED BY A PARALLEL OPERATION OF FEEDERS

"The savings which can be effected by a parallel operation of feeders depend in a large degree upon the design of the transmission system and the ratio of the capacity of the line to the capacity of the individual synchronous converters or transformers which are supplied by this feeder. In one system supplying converters varying from 500 to 4,000 kw. in size together with step-down transformers in substations of 1,500 and 3,000 kw. capacity and also industrial substations on the premises of customers ranging from about 500 to 4,000 kw. in capacity, it was estimated that if the feeders could be operated in parallel then a saving of 20 per cent could be made in the amount of investment. As the installation in question had a book value of about $5,000,000, there was a possible saving estimated at $1,000,000. This company has been operating feeders in multiple for about two years. During this period it has realized nearly 40 per cent of the possible saving in the investment in feeders, and this has been secured by an actual reduction in the number of feeders, notwithstanding a considerable increase in the maximum load.

"The same company also reports in the four years preceding the installation of the relays permitting parallel operation of feeders that they averaged 27 burnouts per year which could not be definitely ascribed to external causes, while in the two years since the feeders have been operated in parallel, the corresponding figure was 16 burnouts. This would indicate a reduction of 40 per cent in the burnouts of cables due to operation of the feeders in multiple, although the cables were actually more heavily loaded. While the time is rather too short to accept these figures as final and conclusive, it apparently indicates that the operation of feeders in parallel reduces the number of troubles due to internal causes."

VARIOUS METHODS EMPLOYED

There are six methods commonly employed to protect parallel tie lines or feeders:

1. Inverse-time-limit relay discrimination.
2. The balanced-protection system.
3. The split-conductor system.
4. The pilot-wire system.
5. The power-directional relay system.
6. The differential-relay system.

Of these six methods, four of them employ simple excess current (overload) relays, the efficiency of the protection depending largely upon the grade of relay employed. The sixth system employs a specially designed current-differential relay as the name implies, while the fifth system, which is one of the most reliable and efficient, employs a power directional relay.

Inverse-time-limit-relay Discrimination.—About the first attempt to protect parallel feeders was made by installing plain-overload or excess-current relays with an inverse-time delay, such as the bellows or induction type, in each line and depending on the inherent division of overload current with the consequent variation in relay-time delay to discriminate and isolate the defective feeder. This system is quite satisfactory where an occasional interruption is not of serious consequences, and where there are a number of parallel feeders, its selectivity increasing with the number of lines.

As an example of how inverse-time-limit relays may discriminate, consider the parallel tie lines in Fig. 145. The generator bus is tied to the substation bus with five three-phase transmission lines, A, B, C, D and E, and these lines are equipped with circuit breakers and relays at both ends.

Now suppose a short-circuit occurs at X. A rush of current flows directly from the generating bus. Say for example it amounts to 10,000 amp. Another rush occurs over the lines A, C, D and E and through the sub-bus, back to the short at X. Say this amounts to 6,000 amp. This is divided between
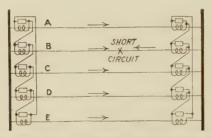
FIG. 145.—Elementary diagram of parallel feeder protection by inverse time discrimination.

the four feeders A, C, D and E, each taking one-fourth so the current in each is 1,500 amp. It is very evident that if all the relays are set equally, the one having 10,000 amp. will go out much quicker than the ones having 1,500 amp. Likewise the one having 6,000 (B from sub-bus) will go out quicker than the ones having only 1,500 amp.

The greater the number of lines, the greater the differences of current during a short-circuit, and the more protection.

Suppose, however, it is not a "dead" short but merely a high-resistance short, making only a moderate overload. This throws the action on an entirely different part of the time curve, and the relays may or may not distinguish which is the defective feeder.

It is very evident that the selective action cannot be obtained from 150 per cent overload to a "dead" short, and since this can be done with power-directional relays, the selective inverse-time-limit-relay system is only employed where low initial

expense is of paramount importance and absolute continuity of service a secondary consideration.

The Balanced Protection System.—When there are a comparatively large number of parallel feeders which may be divided into pairs, quite efficient protection may be obtained by using a simple excess-current (overload) relay, connected differentially to the two lines much in the same manner as that described under differential-transformer protection. In this case, if
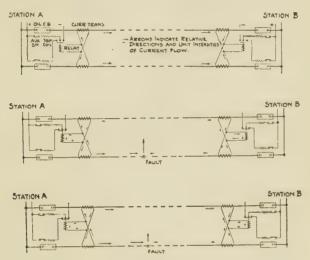
Fig. 146.—Three views of balanced protection of two parallel lines. (Not discriminating.)

trouble occurs in one feeder, then both feeders in the pair go out. If, however, both feeders develop trouble at once, as might be the case if both sets were carried on the same pole line, then neither set would go out unless equipped with suitable reactors; or if equipped with plain overload relays, the whole substation might go out unless there were enough lines to enable the inverse-time-limit relays to trip out the bad feeder by their selective time delay. Consider Fig. 146. The transformer on the first feeder is connected with its secondary in series with that of the other transformer. Normally the currents are as shown by the arrows and no current flows through the relay. Then consider the second figure. A short-circuit has occurred at *X*.

There is an overload on both lines, but the current has reversed as shown; it now bucks the opposite transformer with the result that the two currents from both flow through the relay, which closes and trips out both breakers at station *B*. This relieves the overload on the good feeder, but the overload still exists on the shorted feeder. Consequently, there is again an unbalancing of current in the current transformers at the station *A*, and this unbalancing causes the relay at station *A* to trip out both feeders at station *A*, thereby isolating both feeders at both ends. An open circuit in either line will also cause an unbalancing and tripping of relays.

It will be noted that both substation breakers are tripped no matter on which feeder the trouble occurred, also that if a simultaneous short occurred on both feeders, neither breaker would trip as the current in both transformers would reverse, giving the same effect as normal direction.

This can be overcome by correctly inserting reactances in the substation end in one feeder and in the generator end of the other feeder, as will be more fully explained under the "Split-conductor System."

After the tripping of a pair of lines, it is the customary practice to locate the good line and put it back in service with straight overload protection, in place of the differential protection.

In order to protect against short-circuits on the substation bus itself, or against any possibility which would not cause an unbalancing of currents, or a relative reversal of current on a group of parallel feeders, the generator end of all feeders should be provided with inverse-time-limit relays having comparatively high settings. With this arrangement, it often happens that if the fault occurs on the line between the main and substation, the substation relay clears the fault very quickly at the substation end, so that the inverse-time-limit relay on the faulty line only at the generator end trips, thus leaving the good line of the pair connected at the main station. Then if a voltmeter is connected at the substation to ascertain which line is alive, the good line may be quickly put back in service.

Differential-balance-relay Protection.—In this system, it is necessary to have a large number of parallel feeders or tie

lines in order to secure an unbalanced current in the event of
a short on any line. A relay connected as shown in Fig. 147
consists of two solenoids *A* and *B* each pulling down on plungers
C and *D* which are attached to the rocker arm *E*. This rocker
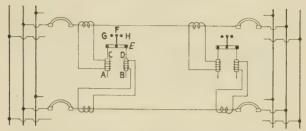
Fig. 147.—Elementary diagram of parallel line protection by differentia
overload relays.

arm carries a moving contact *F* which may make contact with
either *G* or *H* according to which solenoid exerts the stronger pull.

The feeders are arranged in pairs with the current trans-
former of one line connected to solenoid *A* and the current
transformer of the other line connected to solenoid *B*. As
long as both lines carry their share of the load, the pull on both
plungers is equal no matter what the magnitude of the load,
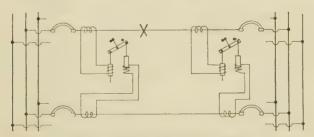
Fig. 148.—Short-circuit on a feeder protected by differential overload relays.

but should a short occur as at *X* in Fig. 148 then the current
is no longer equal, thus allowing one solenoid to overpower the
other and trip the breaker on the defective line. These relays
may be used at the generating end and at the receiving ends
of the line if there are three or more lines entering. Complete

diagrams of instantaneous balance relays and time delay relays
are shown in Fig. 149.

Split–conductor System.—This method utilizes a cable with
two wires in parallel instead of a single wire. A two-phase
cable would thus have eight wires, and a three-phase cable
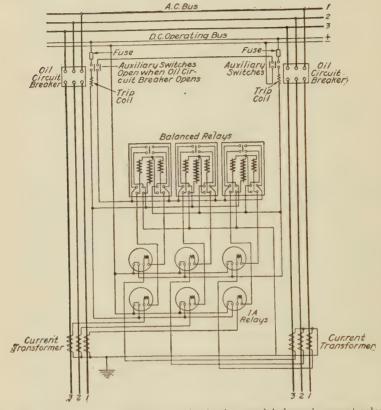
Fig. 149.—Connections of G. E. overload relays and balanced current relays
for protection of parallel lines.

six wires. Figure 150 shows the two wires of one-phase of a six-
wire cable. The other two sets would be connected in a similar
manner. A differential-current transformer is used having
two primaries which buck each other on balanced current and,
therefore, produce no current in the relay during normal opera-
tion. Suppose a defect occurred between the two lines as in

Fig. 151. The currents would no longer divide equally but less would flow in one line than the other. This unbalancing of current would excite the relays and open the breakers at both
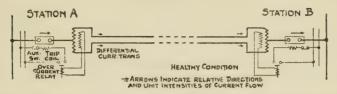
FIG. 150.—Schematic diagram of connections of the split conductor system

ends, effectually isolating the cable. Figure 152 shows the conditions of a low resistance fault.

However, a short only between two sections of the same line would cause no damage; but such a short seldom occurs.

FIG. 151.—Direction of power flow with "short."

Generally one pair short-circuits to another pair. However, if one pair shorted to either wire of another pair, the currents in the two conductors would be unequal and the breakers at both ends would trip out. If, however, the two sections of
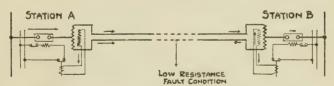
FIG. 152.—Length of arrows represent the intensity of the power through the fault.

the same line shorted together and these shorted to two similar sections, the currents would still be balanced and no protection result. This is overcome by installing a reactance in the lines as shown in Fig. 153. It will be noticed that a reactor is in one

side of the split at one end of the cable and a reactor is in the opposite split at the opposite end.   Now, if both splits short-circuit, the current is no longer balanced, due to the reactor, and the relays trip out the breakers.   For further details see the paper by W. H. Cole, on "Split-Conductor Cables—Balanced Protection," *Proceedings A. I. E. E.*, July, 1918, p. 793.

A short-circuit on one cable naturally overloads all the cables, but if the other cables are intact the current will divide equally in the split conductors and the relays will not be energized, no matter what the overload.   As in the previous example this is excellent protection but is very expensive, requiring
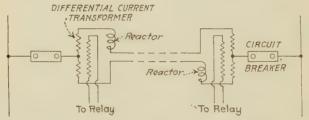
Fig. 153.—Showing the use of reactors in the split conductor system.

reactors and large cables.   The same protection is given by using power-directional relays (to be described later) and this has discouraged the extensive use of the split-conductor system.

The Pilot-wire System.—As has already been shown, differential relays are practically indispensable in protecting transformer banks by instantly cutting out a defective unit without interrupting the service.   Closely allied with this protection is the differential protection of parallel feeders, called the pilot-wire system.

Referring to Fig. 154 the main generating station is tied into the substation by means of several feeders.   Each feeder is equipped with circuit breaker, current transformers and relays at each end.   Parallel to the feeders are two small wires, generally about No. 10 B. & S. gage, connecting the two transformer secondaries and relays in series.   Under normal conditions, no current will flow in the pilot wires as the secondary windings are arranged to "buck" each other, resulting in zero current, regardless of load.   The direction of the current is as

shown by the arrows. But suppose a "short" or other defect occurred between the two stations as at X. Power starts to feed into the short from the generator bus, and, in addition, it feeds over the good feeders, through the substation bus and back into the short-circuit.

Thus, there is a heavy excess current on every current transformer, A and B and G and H. Since the current is normal in the good feeder, the transformer secondaries buck and no
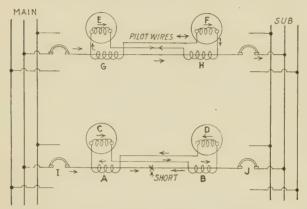
FIG. 154.—Arrows indicate direction of power flow with 'short' on a pilot-wire protected system.

current results in the pilots, no matter how heavy the excess current. The current in A is still in the same direction, but the current in transformer B has reversed. Therefore, it no longer opposes A, but the two transformers unite in forcing a current over the pilot wires and through the relays, which instantly closes their contacts, tripping both breaker I and J, thus effectually isolating the defective feeder, relieving excess current on the good feeders and continuing service without a second's interruption.

If desired, instead of an instantaneous trip, relays may be used which have a time delay inversely proportional to the severity of the disturbance.

Sometimes the feeders are also equipped with plain overload relays in addition to the differential relays, but in that case, the time must always be set longer than that of the differen-

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tial relays, thus enabling them to distinguish between a short in a feeder and an overload in or past the substation.

This method of protection, although widely used in Europe, has not met with much favor in this country, except on small systems where the substations are close together, as the cost of the pilot wires is quite high; besides, the same protection is afforded by power-directional relays, which will be described later.

Another disadvantage of the differential method of protection is that anything which may damage the transmission line would be very liable to damage the pilot wires, and it is very evident that if they become open-circuited, the relays cannot operate no matter how severe the disturbance. Then if the pilot wires become shorted, even though the feeders are intact, the breakers will open.

To this is added the great danger that a high-tension feeder in falling, or breaking, may catch onto the pilot and introduce a dangerous potential into the station.

Pilot-wire systems frequently make use of current transformers with a normal secondary current of $\frac{1}{2}$ amp. with relays wound correspondingly. Thus, if a 300 to $\frac{1}{2}$ amp. transformer were used, and the relay set for $\frac{1}{4}$ amp., the system would clear a ground drawing as low as 150 amp. It has been calculated that if a No. 10 pilot wire is used, these relays can be operated successfully where the stations are between 2 and 3 miles apart, the maximum allowable distance depending upon the setting of the relay, which in turn is determined by the minimum ground current which is expected to flow during trouble. Further information on this subject is given in a paper by R. F. Schuchardt on "Protective Relays," *Transactions A. I. E. E.*, Vol. XXXVI, p. 383, 1917.

Sometimes a loop or ring system contains so many substations that the time intervals, which it is necessary to allow between relays in series, add up to an unsafe amount on the relays at the generating station. If the loop covers a small territory, in may be convenient to install pilot wires between some of the substations. The connections are as shown in Fig. 155 and it will be observed that under normal conditions the current transformers at each end of a conductor are short-circuited

upon each other through the pilot wire. However, the pilot wire may have sufficient resistance so that the current will divide and part of it leak through the relays at each end. Therefore, current transformers are used which have a secondary rating of $\frac{1}{2}$ or sometimes 1 amp., which decreases the potential drop between the two ends of the pilot wire and at the same
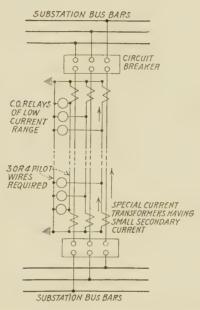
FIG. 155.—Pilot wire system arranged so that secondary current normally circulates between stations.

time requires the use of a relay which operates on a smaller current and consequently has a higher impedance so that less current will leak through it.

When a short-circuit or ground occurs on the line between the two substations, the current transformers at the two ends are no longer short-circuited upon each other, but the currents which they produce are opposed to each other so that current must flow through the relays and trip out the circuit breakers at each end.

PARALLEL-FEEDER PROTECTION BY POWER-DIRECTIONAL RELAYS

This system of protection, which is used extensively on radial-distribution systems, utilizes excess-current relays of the induction type at the generating end of the transmission lines and power-directional relays at the substation or receiving end of the line. Referring to Fig. 156 the generator bus G is tied to the substation bus S by three parallel three-phase lines A, B and C. The excess-current relays and circuit breakers
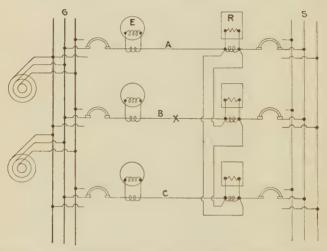
Fig. 156.—Elementary use of power directional relays on parallel feeders Trip and potential connections omitted.

are shown at E and the power-directional relays are shown at R. Now assume a short at X. As has been previously shown, a heavy current flows through the relay on line B, and also, but of less magnitude, on the lines A and C. But the current in relay R on line B has reversed with respect to the bus voltage. Consequently this relay trips out the substation end of this line, relieving the excess current on lines A and C. The overload still continues on line B until excess-current relay E trips out the breaker on the generating end, thus completely isolating the defective feeder. Figures 157a and 157b show the typical connections for power-directional relays

on a three-phase circuit. Figure 157a shows a connection with the current in each relay leading the voltage by 30 deg. at 100 per cent line power factor, and Fig. 157b shows a connection with the current and voltage in any relay in phase with each other. Figures 158, 159, and 160 give typical diagrams furnished by the Westinghouse Co. and the General Electric Co.
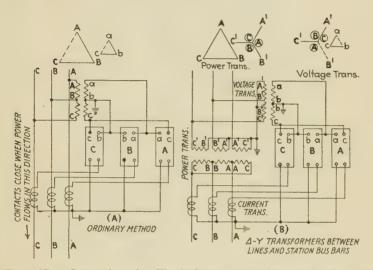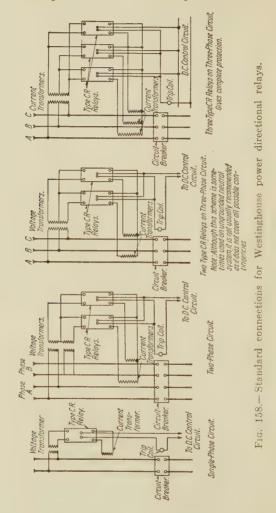
Fig. 157a.—Connections for Westinghouse power directional relays with current leading the voltage in any relay by 30 degrees.

Fig. 157b.—In this diagram, the current and voltage are in phase in each relay at 100 per cent line power factor.

Although this is a simple system, yet the development of a reliable power-directional relay which would function correctly was by no means a simple task. For further information on this, the reader is referred to the chapters on "Power-Directional Relays" and "Characteristics of Electrical Disturbances."

Cross-connected Power-directional Relays.—The use of cross-connected relays is one of the most desirable means of securing discriminating protection under certain circumstances. It also finds ready application on many systems where the feeders are run in parallel between switching points where conditions are so complex that selective timing becomes impossible. The cross-connected system is practically instantaneous

in operation if desired, but it may be provided with any time delay desired by means of the setting on the excess-current members of the power-directional relays.

Fig. 158.— Standard connections for Westinghouse power directional relays.

Another advantage of the cross-connected system is that the relays may be set to clear a fault which draws less than full-load current on each feeder. This enables the correct clearing of trouble on a system having the neutral grounded

through such a high resistance that the total load and trouble current may be less than the maximum load current of that cable.

If the parallel feeders happen to be on a system with more than one generator station, there may be occasions when the power flow is first one way and then in the opposite direction. With the ordinary connections, this often necessitates a change
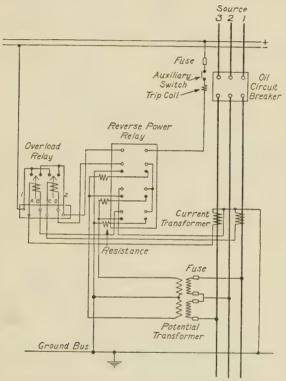
FIG. 159.—Connections of G. E. polyphase power directional relay and overload relays for protecting a three-phase system with ungrounded neutral.

in the relay settings, but with the cross-connected system, the need for this change is obviated, as the adjustment is the same regardless of the direction of power flow.

Some manufacturers and users claim that the cross-connected system is more economical than the split-conductor or the pilot-wire system, because it does not require extra cables. They also claim it to be superior to the balanced protection

using two-in-pair, because the cross-connected system cuts out only the defective feeder, while the balanced system cuts out both feeders, and the good one must be located in some other manner before it can be put back in service.

The schematic diagram of Fig. 161 shows the connections of cross-connected reverse-power relays applied to a system
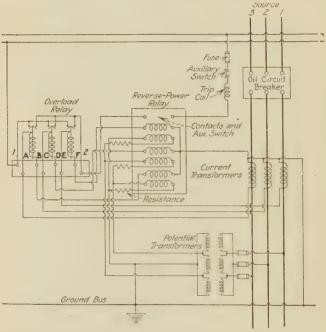
Fig. 160.—Connections for G. E. polyphase power directional relay and overload relays for protecting a three-phase grounded neutral circuit.

consisting of a generating station and a substation connected by two parallel feeders. To simplify it, the diagram shows only one phase of each feeder. A complete diagram for a pair of three-phase feeders is shown in Fig. 162. Here, however, the tripping circuit is omitted.

It should be borne in mind that, while shown in Figs. 161 and 162 for a comparatively simple condition, this scheme can be used with equal success in any part of a complicated network. While, preferably, the cables in the parallel system

should be alike, if there is a difference in their impedance this difference can be compensated for by simple means.

Under normal conditions, the load in each of the cables will
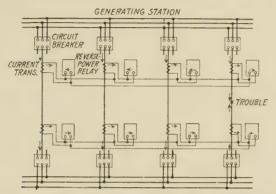
FIG. 161.—Schematic diagram of Westinghouse cross-connected relays with connections for one phase only shown. Voltage and trip circuits omitted for clarity. Arrows show direction of power flow with "short" on right-hand feeder.

be the same and, since the relays have a higher impedance than the current transformers, the current from the latter will, therefore, circulate through all of them in series without any flowing
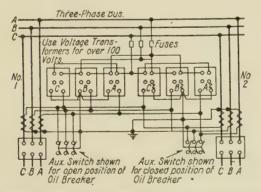
FIG. 162.—Connections similar to Fig. 161 but with trip circuit connections omitted.

through the relays. If the trouble occurs at any point outside the section protected by these cross-connected relays, the current through the cables will still be balanced and conse-

quently there is no force tending to operate the relays.   On
the other hand, if trouble occurs on a cable within the section,
the current through the defective cable will be higher than that
in the others and the excess current from its current transformers
must, therefore, pass through the relays.   While, under this
unbalanced condition, current   will flow through all the relays,
it will be observed that the current is in the proper direction
to cause the relay to act only in the relays at each end of the
defective cables.

In Fig. 162 are shown pallet switches connected in the trans-
former secondary circuit.   These are also connected mechan-
ically to the operating mechanism of the breaker so that when
the breaker opens the current transformers on the feeder con-
trolled will be short-circuited.   By this method a cable can
be cut out of service without interfering with the electrical
balance in the current-transformer circuit.
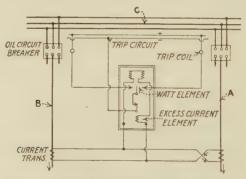
Fig. 163.—Connections of Westinghouse double contact relay (shown for one
phase only).

Differential-power-directional or Double-contact Relays.—
It will be noticed that when the cross-connected relays are applied
to two parallel feeders, they are actually in parallel, and one closes
with power in one direction and one with power in the other.

Therefore, instead of using two relays, it is possible to put
two contacts on the upper element to perform the same duties.
Thus, if the disk turns to the right, it closes one contact and
if it turns to the left, it closes the other contact.

This is clearly shown in Fig. 163, which shows two lines,

feeding from or to the bus C. The transformers are differentially connected, *i.e.*, if the load is divided normally, the current merely circulates through the transformer secondaries and will not pass through the relay, as there is as much tendency to flow one way as the other.

But should one current reverse, due to a short-circuit, there is an immediate flow of current in the relay and its direction is such that it causes the upper disk to turn in the proper direction to close the contacts, which trips the breaker on the defective line. This is true whether the power is flowing into or out of the bus. It is the reversal of current with respect to the bus voltage that determines which way to trip.

As before, Fig. 163 shows only the protection of one wire, but it must be remembered that the others are similarly protected with the voltage connected to the bus which gives a normal lag of voltage 30 deg. behind the current at 100 per cent power factor. The necessity of this, as well as the method of determining the correctness of this phase relation, has been discussed previously.

DISADVANTAGES OF CROSS-CONNECTED SYSTEMS

The use of cross-connected relays or double-contact reverse-power relays has the same disadvantage as any other balanced scheme in that trouble that occurs on the busbars or on all the feeders simultaneously cannot be automatically cleared.

Another disadvantage is encountered when an attempt is made to cut in a new feeder. Assume that the feeders are heavily loaded and arrangements are being made to switch in a new one. If the attempt is made to close the switch on the substation end first, the new feeder will be tripped out, whereas, if it is first closed in from the generating station end, the feeders carrying the load will be tripped out. When only one line is in service, the chance of tripping out the new line while switching it in from the substation end is the same as the chance of tripping out the loaded line by doing the switching from the generator end, but in either case there is no danger unless the loaded line is carrying a current twice as great as the relay setting. As the number of lines in service is increased the

possibility of tripping out the new line at the substation be-
comes greater, while the possibility of tripping out the loaded
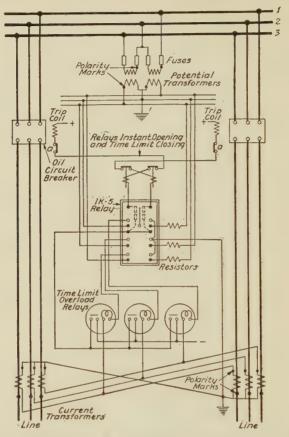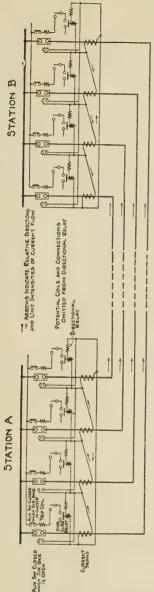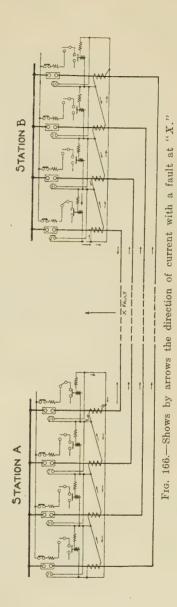
Fig. 164.—Connections of G. E. overload relays, double contact power direc-
tional and auxiliary relays for protection of parallel lines.

lines at the generating station becomes less as shown by the
following table:

Number of lines in service	Number of times load-per-feeder must be greater than relay setting in order to trip breaker	
	at substation	at generating station
1	2	2
2	$1\frac{1}{2}$	3
3	$1\frac{1}{3}$	4
4	$1\frac{1}{4}$	5

Fig. 165.—Balanced protection for three or more parallel lines. (Discriminating.)

Fig. 166.—Shows by arrows the direction of current with a fault at "X."

The same trouble is likely to be encountered in case one line should be opened accidentally. The obvious remedy for this condition is to give the overload elements of the relays so high a setting that the normal-load current cannot possibly operate them.

By doing this, however, the previously stated advantage of setting relays to trip on a fault current less than full load is lost. It then becomes necessary to choose which gives the most desirable protection. The possibility of tripping out the breaker when a new feeder is cut in can also be overcome by mechanically holding the substation relay of that feeder, while cutting in first at the substation and then at the generating station.

Another method of protecting parallel feeders by the differential method is shown in Fig. 164. This method uses a polyphase double contact power directional relay in connection with three overload induction type relays. There are in addition two auxiliary relays in the trip circuit which, as will be seen from a study of the connections, prevent the tripping of the second breaker (after the first has tripped) due to the rebound of the disk in the relay.

Additional diagrams illustrating the connections of a power directional relay and over-current relay are shown in Figs. 165 and 166.

PROTECTION OF RADIAL, RING AND NETWORK SYSTEMS

One of the most important uses of the protective relay is to localize and isolate a defective feeder or piece of apparatus in a radial system of transmission, whether the transmission be confined to small units in one building, or a system covering miles of lines. The principle of application, and desired result, is all the same. A radial system is one in which there
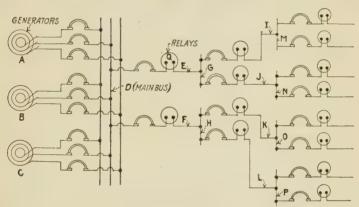
Fig. 167.—One-line diagram of simple radial system.

is a main generator or generators, feeding a main bus (sometimes sectionalized), which in turn feeds several smaller busses; these in turn each feed several more feeders or machines, and so on. Each subdivision is protected by circuit breaker and overload relays. Figure 167 shows the diagrammatic layout of a radial system. In A.C. transmission three-phase is generally used, but instead of showing the three wires in the diagram, the three wires are represented by a single line.

The main generators, A, B, and C, supply the main bus D with energy. From this bus are shown two three-phase

lines E and F, which in turn supply the busses G and H.   In general practice there will be a large number of lines taken from bus D but for the sake of clarity only two are shown.   The busses G and H may be in substations many miles away and E and F long-distance, high-tension transmission lines, or G and H may be distribution boxes in a factory or power plant and E and F a few feet of cable or bus.

Tapped off the busses G and H are lines I, J, K and L, which supply busses M, N, O and P.   These busses have more feeders tapped on.   Although at each subdivision only two lines are
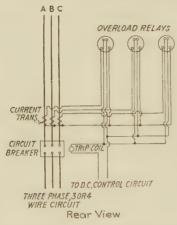
Fig. 168.—Complete diagram of each relay shown in Fig. 167.

shown, it must be remembered that the number of lines is unlimited electrically.   For instance, bus G might supply a dozen feeders, and bus H might supply another 20 or 30 feeders and busses.

Immediately as each line leaves the bus, it is supplied with a circuit breaker and right after the circuit breaker comes a current transformer which actuates an overload relay, which in turn is arranged to trip the breaker.

As stated before, the line E represents three separate wires in actual practice.   The relay is in reality three separate relays operated from three current transformers, and the circuit breaker is a three-pole breaker.   In other words, if Fig. 167 were fully drawn out, each feeder, relay and breaker would

look like Fig. 168, which plainly shows the three lines A, B and C, the current transformers, relays, circuit breaker and trip connection.

Now, suppose a short-circuit or rather a heavy overload occurred on one of the feeders going from bus N, the overload extending all the way back to the generators as shown in Fig. 169 by the heavy black lines.

Relays Z, T and Q would be affected, and if they were all set the same, all three breakers would go out. This would kill
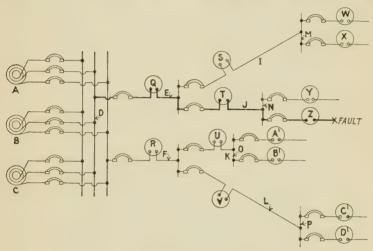
FIG. 169.—Heavy line shows path of overload with fault at "X."

everything connected to line E. Therefore, breaker on line E must not go out if a short occurs on line N. Neither must J go out. Only the line in which the short-circuit occurred must go out.

Therefore, all relays connected to lines leading from busses N, M, O and P must trip before relays connected in lines I, J and L. Then relays in these lines must trip before relays in lines E and F.

The problem, then, is to select a relay which may be set to give this selective-time action. Let us first consider the curves of an inverse-time-bellows relay, as shown in Fig. 170. It is very evident that with various settings the time will vary.

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Say that relay Q is set according to curve 3, relay T curve 2, and relay Z curve 1. Now suppose the overload amounted to 200 per cent of full load. Relay Z trips first (in 2 sec.); relays T and Q would require 4 and 6 sec. respectively. So the action is perfectly selective at 200 per cent load.

Suppose the overload was 400 per cent. Relay Z still trips first (in $\frac{1}{2}$ sec.). But an actual short-circuit might draw about 2,000 per cent or in any case over 1,100 per cent load. Consider the curves at this point. They intersect. Therefore,
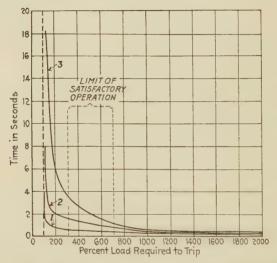
Fig. 170.—Time load curves of a Westinghouse bellows type overload relay.

the action is no longer selective, but at heavy overloads the action is almost instantaneous. Therefore, relays having curves similar to Fig. 170 are not suitable for radial protection.

Definite Time.—Let us consider the definite-time-limit relay. Relay Z may be set for 1 sec., relay T for 2 sec., and relay Q for 3 sec. It is now evident that no matter what the overload, if the relays act according to their setting, the most distant feeder will go out first. So it would seem that a definite-time-limit relay should be satisfactory.

But it is not necessary to trip a 150 per cent load as quickly as a short-circuit. Nor is it well to sustain a short on line

E for 3 sec.   The obvious remedy is to set the time closer.   However, there may be four or five subdivisions of the radial system and practice has shown that it is useless to depend on a bellows relay for such close time.   In the first place, it takes considerable time to test and set the correct time, and then it is not permanent as the leather often dries out and changes the time so that at a critical moment the relay will not isolate its feeder line properly.

Inverse-definite-minimum Time.—Evidently, the lines must be protected by an easily-set, permanently-accurate relay and one which combines the features of an inverse-time-limit relay at
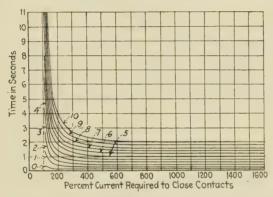
Fig. 171.—Time load curves of a Westinghouse induction type overload relay.

moderate overloads with those of a definite-time-limit at heavy overloads.   The induction relays described in a previous chapter meet these conditions very satisfactorily.   Consider the curves of the induction relay shown in Fig. 171.

Say relay *Z* is set according to curve 3; relay *T* to curve 8, and relay *Q* to curve 10.   Consider 150 per cent load.   Relay *Z* trips in 1.3 sec.   The time is now selective.   The farthest relay takes 0.5 sec.; the next 1½ sec.; the next 2 sec.   Thus the time is always selective with a relay of this type.   Figure 172 gives curves of another type of induction relay.

Minimum Time.—The next question is, how many lines or subdivisions can be protected, or in other words, how close can the settings be and still have accurate selective action.

It is not safe to sustain a short-circuit more than 2 sec. on the generator; this limits the first division to 2 sec. The last subdivisions may be instantaneous. The number of divisions
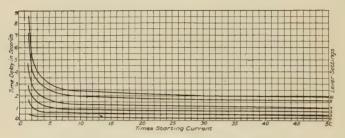
Fig. 172.—Time load curves of a G. E. induction type relay.

in between depends on the accuracy of the relay and the time it takes the breaker to open.

Figure 173 gives the time taken by various breakers between the instant of tripping and opening of the circuit which relieves the overload. It will be noted that 0.3 sec. is a fair value to allow.
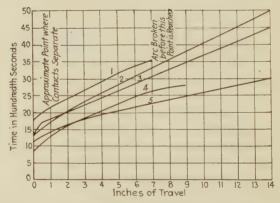
Fig. 173.—Typical time characteristics of oil circuit breakers.
(1) 15,000 volts, 2000 amperes. (2) 88,000 volts, 300 amperes. (3) 66,000 volts, 300 amperes.

Therefore, if the relays were perfect, each subdivision could be set with 0.3 sec. to maintain selective action. But the time of the circuit breaker may vary slightly, so it is better to allow 0.4 sec. Then allow 0.1 sec. for any inaccuracies

which may occur in the relay. This makes 0.5 sec. about the lowest difference which can be depended on.

If the main relays Q and R are set for 2 sec., then S, T and U and V may be set for $1\frac{1}{2}$ sec.; W to Z and A' to D' for 1 sec. The next division would be set for $\frac{1}{2}$ sec. and the next division for instantaneous trip.

In this manner a radial system may divide four times and each division will be thoroughy protected and will not cause interruptions to any good feeder between the bus supplying the defective feeder and the main generators.

Parallel Feeders on Radial System.—It is very evident, with the simple scheme just described, that if an accident
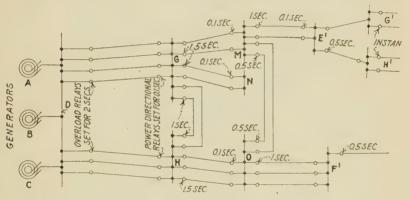
Fig. 174.—Radial system of parallel feeders. (One-line diagram.)

occurred on feeder E, which caused an interruption, then every further division would also be interrupted. To avoid this, instead of tying bus G to bus D (Fig. 167) with a single line, there would be two or more parallel tie lines, protected as described under "Protection of Parallel Feeders." The same protection by parallel feeders also applies to all other feeders such as F, I, J, K, L, etc.

In one system, overload relays are installed every time a line leaves a station and reverse-power relays installed on every line that enters a station. The overload relays are set for decreasing time as, for instance, those leaving bus D for 2 sec.; those leaving bus G for 1.5 sec.; and bus M for 1 sec.; and considering a more complete layout as shown in Fig. 174,

set E' and F' for 0.5 sec. and G' and H' instantaneous. The reverse-power relays are set very close, for instance, about 0.1 sec. Now if a short-circuit occurs on any line, the reverse-power relays kick out the breaker at the receiving end in 0.1 sec. If the short had occurred on a feeder between G and M, the overload relays at G would finish isolating the shorted feeder in 1.5 sec., leaving the good feeders to handle the load without a second's interruption. If the short had been between D and G, the reverse-power relays would have isolated one end of the defective line in 0.1 sec. and the relays at D would have isolated the other end in 2 sec., again allowing the good feeders to assume the total uninterrupted load.
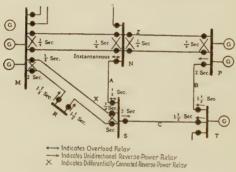
Fig. 175.—Radial system forming network.

If, however, all the lines between D and G should become shorted, as might be the case if all were carried on the same pole line, then the stations G, M and N and all their loads would be dead, unless other means were taken to supply them. Suppose station G, instead of being diametrically opposite to station H, should be about an angle of, say, 30 or 40 deg. It would not cost much to have a line run from G to H. Then if all the lines from D to G go out, the stations G, M and N would be fed over the tie line between H and G. In a similar manner, if the lines between D and H went out, then H's load is assumed by G.

In a similar manner, a line may run from M to O, so even if all the lines from D to G, or from G to M, or if G itself goes out of commission, the rest of the system is still supplied.

It will be noted that power may flow from G to H and from H to G; or from M to O and from O to M. To protect these feeders properly as well as to protect any parallel feeders in which the power may flow in either direction, the power differential relay is used. This does not discriminate between direction of power flow as long as the load divides equally between the two lines. But if the power in one line reverses due to a short in that line, the relay immediately detects it and trips that breaker. Another typical network system with its time setting is shown in Fig. 175.

The Ring System.—When several substations are fed from one main generating station, and their geographical location is favorable, the ring system forms one of the best ways of securing uninterrupted service with a minimum of expense for feeders, etc. The ring system in its elementary form has been treated under the chapter on "Applications of D.C. Power-Directional Relays," while the conditions of service experienced such as low voltage and phase distortion have been treated under the chapter on "Characteristics of Electrical Disturbances."

While theoretically it is possible to include any number of substations in the ring, yet in actual practice the number is limited to four or five for two reasons: First, the best relays made will not select with absolute precision closer than $\frac{1}{2}$ or $\frac{1}{3}$ of a second, and second, the maximum time that a "short" should be held on before clearing is about 2 sec. Of course, this rule is not rigid, but represents the best practice.

Let us consider the elementary ring again as shown in Fig. 176. There is a main generating station at A with substations at B, C, D and E. Although the transmission line is shown by a single line, for the sake of simplicity, yet it will be understood that each line if drawn out with transformers and relays would assume the appearance of the insert. At station A, the lines are protected by simple, accurate overload relays, while each substation has A.C. power-directional (reverse-power) relays at both ends. These relays are set so that they will never trip when power flows into the substation no matter what its magnitude, but will only trip when an overload flows away from a substation.

Going around the ring in the direction A,B,C,D,E, the relays

on the furthest side of each station are set with decreasing time element; for instance $A = 2$ sec., $B = 1\frac{1}{2}$ sec., $C = 1$ sec., $D = \frac{1}{2}$ sec. and $E =$ instantaneous. Going around in the direction A,E,D,C,B, the relays on the outgoing sides would be set as follows: $A = 2$ sec., $E = 1\frac{1}{2}$ sec., $D = 1$ sec., $C = \frac{1}{2}$ sec., $B =$ instantaneous.
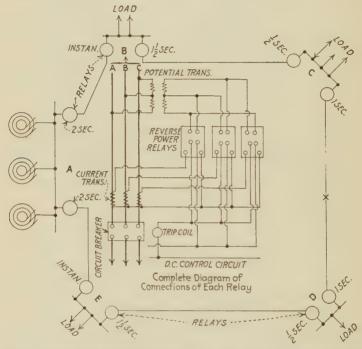
Fig. 176.—One-line connection diagram of the ring system. Insert shows the complete diagram of connections at each station.

Now remembering that a relay starts to function only when the power flows away from a substation, consider the effect of a "short" at X. Power starts to flow from A through B and C into X and also through E and D into X. Thus the relays on the far sides of B and C start to operate, but as C is set for 1 sec. and B for $1\frac{1}{2}$ sec. it is evident that the breakers at C will open and relieve the "short" from both B and C. On the other side of the ring, the relays on the far side of E and D start to operate, but since D is set for 1 sec. and E for $1\frac{1}{2}$ sec. it is again

evident that the breaker at D will open, thus relieving the "short" on both D and E, and disconnecting only the faulty line between C and D.

A further study of a "short" at any point on the system will disclose the fact that this arrangement will localize and disconnect only the faulty line or substation and leave the rest of the ring intact.

Parallel Feeders on Ring System.—When parallel feeders are used between substations on a ring system, the power-directional relays not only afford protection to the parallel feeders but also serve to maintain the ring intact by isolating the defective feeder. In ordinary parallel-feeder protection the power-directional relays were set to operate almost instantly in order to cut out the defective feeder as soon as possible, but when applied to the ring system, the relays must be set with a decreasing time element as previously described.

Rings With More Than One Source.—If, in a ring system, one of the substations should be capable of generating at certain times as, for instance, might be the case where a substation was provided with a water turbine to take advantage of waterpower when avaliable, then the relay setting becomes a matter of considerable study of load division. If, however, this substation assumes the total load of the ring, then it is only necessary to set the relays with decreasing time element from this station. As this may be done at telephoned instructions from the load dispatcher, it emphasizes the necessity of a relay which can be quickly and accurately set without elaborate tests.

PROTECTION OF NETWORK SYSTEMS

The subject of the protection is so broad and so varied that but little of a general nature can be said here. Each network system offers a deep, analytical study by a competent engineer, who can take into consideration and correctly weigh all the variables such as division of loads and overloads, short-circuit currents, phase distortions, and other accompanying effects. Even then, there may be conditions which cannot be accurately predetermined except by the actual construction of a miniature system having the electrical characteristics of resis-

tance, inductance and capacity of the original lines and determining the divisions of load from this miniature system.

In actual operation, it will usually be found that there are several feeders or substations which may be isolated in an effort to locate the trouble, if it is not isolated by automatic protection. This condition may be obtained by having a number of breakers open at the first instant of trouble. For instance, in Fig. 175 is shown a feeder between stations N and S which is used most for maintaining correct-voltage regulation. In case of trouble, however, it would be possible to dispense with this until the trouble was cleared up on the rest of the system. We have, therefore, assumed that the circuit breaker on section A in the substation is equipped with an instantaneous relay. If it should happen that the trouble is on this section of line the relay in station S will operate after $\frac{1}{2}$ sec. and clear the trouble; but if the trouble is not on this particular feeder, no harm will be done and the load that is supplied from it will not be interrupted. In order that synchronizing and other switching on the system shall not cause interruptions, it is assumed that the minimum time limit of $\frac{1}{4}$ sec. is necessary. If such a setting is used, and a short-circuit occurs at the point Z, the relay in substation N will require $\frac{1}{4}$ sec. to operate, and there will be a further $\frac{1}{4}$ sec. required for the circuit breaker to open. The relays at substation P will not begin to operate until the switch at substation N has opened, because it is assumed that the short-circuit is close to the latter substation and there is, consequently, no unbalancing at substation P. There will, therefore, be still further delay of $\frac{1}{2}$ sec. at substation P before the trouble is finally cleared. It is for this reason that the definite time limits in the tie feeders between substations P, S and T have been shown to be higher than appears necessary at first sight. With the setting shown in these substations it will require more than 2 sec. to clear a case of trouble should it occur in either section B or C. For this reason it may be thought advisable to adjust the relays at substation T so that they have a lower time setting, with the result that one of them will operate on practically all cases of trouble, but, as in the case of section A, this will not result in any interruption of service; it will merely trip out a circuit breaker that can later be closed by the attendant

These illustrations show how to adapt relays to complicated systems, thus securing all the advantages which can be obtained from a close interconnection of stations and substations.

PROTECTION OF SYSTEMS BY UNDER-VOLTAGE AND EXCESS-CURRENT RELAYS

Another system successfully employed to protect a ring system utilizes a combination of under-voltage and excess-current relays. In this system all the breakers at each sub-station are mechanically locked in closed position, and this lock can never be opened by excess current but only by low voltage. When the voltage falls to a certain predetermined value, generally about 70 per cent of normal, the under-voltage
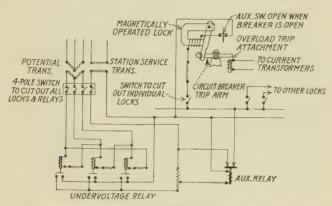
Fig. 177.—Connection diagram for protection by over-current and under-voltage relays.

relay operates and opens the lock on the breaker; then an excess current operating the excess-current relay is free to trip the breaker. The object of this arrangement is that the voltage will fall only in the immediate vicinity of the short-circuit, so although the short-circuit current extends all the way back to the generators, yet only the breakers in the immediate vicinity of the short-circuit will be unlocked and allowed to trip upon the excess current.

When stations are quite close together, the breakers in an unaffected section may sometimes be unlocked on the occurrence

of a heavy disturbance, but in this case, the short-circuit will usually be localized by the inverse-time-element selectivity of the excess-current relays, which will clear the trouble before the other relays trip the unlocked breakers.

Figure 177 shows the diagram of connections of this combination. The potential transformers supply the under-voltage relays which normally have their contacts open. The auxiliary relay is energized by a service transformer and this relay in turn operates the electrical locks on the breaker using the same transformer for its energy supply. Both the auxiliary relay and the locks on the relays are normally energized and are de-energized either by the functioning of the under-voltage relays or the loss of station voltage. As is shown in the diagram one set of relays may control a number of circuit-breaker locks, and each lock is provided with an individual cut-out switch and a pallet switch to open its circuit after functioning.

When the line potential drops to a predetermined value, one or more of the under-voltage relays close their contacts, thus de-energizing the auxiliary relay, which in turn de-energizes the electrical locks on the breaker, thus releasing the latch and leaving the breaker free to be tripped by the excess-current relays. If the voltage does not fall low enough, then the breakers cannot be opened by an excess current.

MISCELLANEOUS RELAYS

Over- and Under-voltage Relays.—Oftentimes there are conditions of abnormally high or low voltage which may lead to disastrous results if not promptly detected and corrected. Considerable damage might easily be done by an increase in
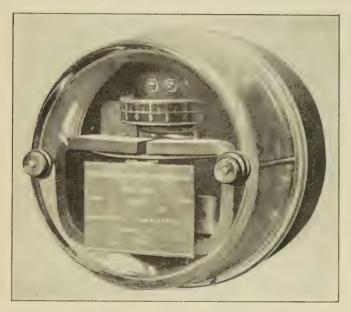
Fig. 178.—Induction type, over- and under-voltage relay. (Westinghouse.)

voltage burning out lamps. This increase may be due to a number of causes, such as the failure of a Tirrill regulator on the generator, or a short-circuit in the generator field resistor, etc. Then, on the other hand, the voltage may drop low, and even if this drop did not lead to disastrous overload results, it might cause considerable annoyance due to lamps burning dim or motors running slow.

To give warning of such abnormal conditions, or actually to disconnect a circuit, should practice so determine, an over-voltage or an under-voltage relay may be installed. Such a relay is shown in Fig. 178. It is the same in construction and principle of operation as the previously described overload relays, except that the windings are wound to stand the impressed voltage. In the over-voltage relays, the contacts close when the voltage exceeds a certain predetermined point, which either trips a breaker, rings a gong, or gives some other signal to the operator that the voltage is too high and requires attention.

The tripping voltage may be varied over wide ranges generally between 75 per cent and 160 per cent of normal, and a time delay may be obtained if desired. So if a circuit is normally running at 110 v., it becomes possible to trip it, or ring a bell, if it goes to 115 or 120 v. or higher.

In the under-voltage relay, the windings are arranged so that the voltage tends to keep the contacts open. Then should the voltage drop to 75 or 80, or whatever the relay is set, there is no longer torque enough to hold them open, so they close and generally sound an alarm.

Fig. 179.—Solenoid type under-voltage relay. (General Electric.)
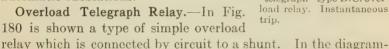
The Solenoid Relay.—The solenoid principle as well as the induction principle may be used to indicate the conditions of over-voltage and under-voltage, but its action is much rougher in adjustment than the induction. In the over-voltage relay the plunger is arranged to move upward and close contacts on over-voltage. On the under-voltage, the solenoid normally holds the plunger up and contacts open, but on a fall in voltage, the plunger drops and the contacts close. A solenoid relay is shown in Fig. 179.

In connecting, the potential circuit is connected directly across the line, like a voltmeter; or in the case of high-tension work it is connected to the secondary of the potential transformer.

Under-current Relays.—In such circuits as the constant-current arc system, some signal must be given if the current drops too low. In other places there may be conditions which require an indication of low current. To provide this, a regular induction-type relay is used, except that the current tends to keep the contacts open. Then if the current drops to a certain predetermined value there will no longer be enough current to hold them open, and thus they close and give a signal or trip a breaker. These relays are also used to shut down automatic substations.
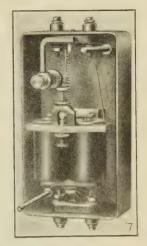
FIG. 180.—Westinghouse "telegraph" type D.C. overload relay. Instantaneous trip.

Overload Telegraph Relay.—In Fig. 180 is shown a type of simple overload relay which is connected by circuit to a shunt. In the diagrammatic scheme of parts, Fig. 181, the iron armature A, carrying the contact B and pivoted at C, is held in its normal position (contacts B and D open) by the tension of the spring E. This spring is attached to an adjustable arm F secured to the frame G by the thumbscrew H. Arm F carries a scale calibrated in millivolts. The arm that carries contact D is insulated at I from the main frame G. The terminals K and K' of the coil J are connected to a shunt which is in series with the line, and therefore takes a current proportional to the main current. If the relay is set for 50 m.v., then, when the current in the shunt produces a drop of 50 m.v. the

FIG. 181.—Schematic diagram of overload "telegraph" type relay.

armature A is attracted, closing the contacts B and D, which closes a circuit from L and L, to the circuit breaker's trip coil.

Figure 182 gives the diagram of connections of the relay and circuit breaker under normal load, the path of the currents being shown by arrowheads. An overload causes the relay contacts to close the trip-coil circuit to the breaker and the latter opens the circuit, thus relieving the overload on the system. In installations where the potential trip-coil circuit is connected to the circuit to be controlled, the overload trip
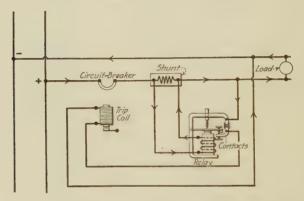
Fig. 182.—"Telegraph" type relay connected in the circuit.

attachment on the breaker should always be connected in the circuit, since dead short-circuit on the line may cause the voltage to drop so low that it will not operate the potential trip coil on the breaker. This allows the overload attachment on the breaker to be set high, for protection against short-circuits or other violent disturbances, but the relay is set so as to give protection against moderate overloads.

PROTECTION AGAINST REVERSED PHASE

If a three-phase motor is disconnected from a circuit and the phases reversed when it is reconnected it will, naturally, run backward. Such a reversal may occur, and has occurred, when the motor is disconnected for repairs, through an error in reconnecting loads at the power house, or substation, or from a number of other causes.

In many cases the reversal of rotation of a motor, aside from the inconvenience it causes, is not a serious matter as the error can be corrected at the motor terminals. In other cases, however, serious consequences may result. The reversal of an elevator motor, for instance, might result in wrecking the machinery and loss of life.

To protect motors against phase reversal where such protection is necessary, the reverse-phase relay has been developed.

Fig. 183.—Reverse-phase relay. (Westinghouse.)

This is shown in Fig. 183. The parts are all identical with the overload-induction relay with the exception of the windings. The main coil is a voltage coil exactly like a watt-hour meter, and the series coil is of heavy wire, connected to the secondary of a small step-down transformer. Since one coil is tapped on one phase and one on the other, they have the necessary phase displacement to produce a shifting field, which reacts on the disk. The external connections are shown in Fig. 184. Nor-

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mally, the voltage tends to rotate the disk to the right and keep the contacts open.   But should one phase be reversed, or should one phase fail, or should the voltage drop below 75 per cent of normal, then the contacts close and open a breaker.   Reversal of a phase actually reverses the direction of rotation, causing the contacts to close very quickly.   This relay will not prevent a three-phase motor from running single-phase if one phase opens while running.   It will, however, prevent the motor
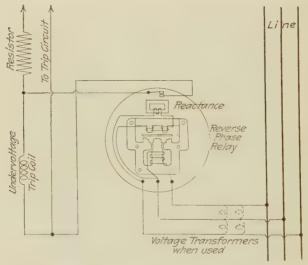
Fig. 184.—Schematic diagram of connection for reverse-phase relay.

from starting again.   In the case of an elevator motor this is an advantage as it allows the car to run to a floor and stop even though one phase should open while the car is between floors.

Service-restoring Relays.—There are many cases in which it is necessary actually to open the breaker to clear a short-circuit as, for instance, an arc across two lines, which is killed the instant the breaker opens.   This permits the feeders to be put back in service immediately.

If the circuit breaker is reclosed automatically within a second after the transient trouble has occurred, the service will be restored in time to prevent induction motors from stalling.

The service-restoring relay system has been developed to perform this operation within the shortest possible time and thus reduce all disturbances to a minimum, thereby greatly improving the service. Should a permanent defect occur, the system will allow the breaker to remain open until the defect is cleared.

A schematic diagram of operation is shown in Fig. 185. Any type of overload relay may be employed to trip the circuit
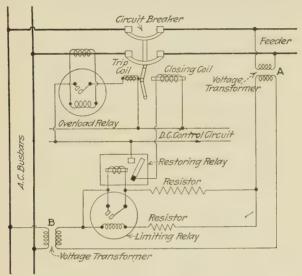
Fig. 185.—Connections of automatic service-restoring system.

breaker on overload as previously described. A voltage transformer on the feeder outside the circuit breaker is connected so that its potential opposes that of another voltage transformer connected to the busbars. The restoring relay, which is similiar to a magnet switch, is connected in series with these two voltage transformers. Before a short-circuit occurs, both voltage transformers are subjected to the same conditions so that no current will flow through the restoring relay; but when a short-circuit occurs and the circuit breaker has been opened by the overload relay, current will be forced by the busbar transformer *B* into the feeder transformer *A*, through the restoring relay. The restoring relay will then close its

contacts, which, in turn, will close the circuit breaker, which, of course, must be of the electrically closing type as well as electrically tripping.

In case of a permanent defect on the feeder, the restoring relay would continue to open and close the circuit breaker indefinitely, as each time the breaker closes, the overload relay opens it. To prevent this, a limiting relay, similar to the over-voltage relay, but equipped with weaker spring and heavier damping magnets so that its action is sluggish, is connected
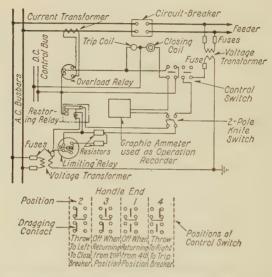
FIG. 186.—Complete diagram of connections, showing control switch, graphic ammeter, etc.

in such a manner that while the circuit breaker is open it is subjected to the same difference of potential that is operating the restoring relay. Every time the circuit breaker opens, the limiting relay contacts begin to close and, due to its heavy damping, they do not return to the starting point immediately after the circuit breaker is closed. After the circuit breaker has opened and closed a predetermined number of times, this relay closes its contacts, thus short-circuiting the restoring relay and preventing further operation.

This system is often installed at substations having no

attendant. In that case it is often found advisable to have an indicating device that will show when the service has been momentarily interrupted. For this purpose, a graphic ammeter is placed in the direct-current control circuit of the circuit breaker. This will indicate whenever the breaker has been closed by automatic means. Complete diagrams are shown in Fig. 186.

When this system is used, and provision is made for tripping the breaker manually by a control switch, contacts are arranged
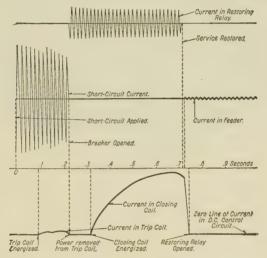
Fig. 187.—Oscillograph record showing operation on a transient "short."

on the control switch which automatically open the circuit between the two voltage transformers, which prevents the breaker from resetting immediately after it is tripped.

Figure 187 shows an interesting oscillograph record of the behavior of the various parts. The time is shown on the third horizontal line. The second horizontal line shows the great intensity of the short-circuit current. At the end of 0.1 sec. the fourth line shows the relay has acted and the trip coil is energized. At the end of another 0.1 sec. the breaker has opened, thus decreasing the short-circuit current to zero (second line) in a total of 0.2 sec. Instantly the service restoring relay is energized (first horizontal line) and in 0.1 sec. it closes its con-

tacts, thus energizing the closing coil of the breakers. This takes considerable current and 0.4 sec. as will be seen from the fourth line. Immediately on the closing of the breaker, the current in the restoring relay ceases (first line); the closing coil is de-energized and the current continues normal in the feeder as shown in the second line.

Thus it will be seen that only 0.7 sec. is required from the first instant of overload to the instant of resumed service.

If, however, the short-circuit is not removed upon the opening of the breaker, then when the breaker recloses, the short-circuit
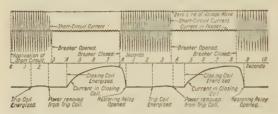
FIG. 188.—Oscillograph record showing operation on a permanent "short."

current immediately operates the overload relay and again trips the relay until the sluggish limiting relay prevents further action.

This is plainly shown in Fig. 188, where the short is shown interrupted as before, and the breaker closed again, but instead of resuming normal current, the current is again excessive as shown.

The service-restoring system has proved its effectiveness in many cases and is recognized as an invaluable aid in securing cheap, efficient and effective service.

Bell-ringing Relays.—If a circuit breaker is tripped out, and the station attendant, instead of being near at hand where he can see and reset it, is some distance away, a bell-ringing relay may be used. This must ring the bell or alarm until some notice or action is taken if the breaker opens due to the protective relays tripping, but it is not necessary to ring the bell if the breaker has been opened intentionally. The relay shown in Fig. 189, with the cover removed, will meet the foregoing requirements. A schematic connection diagram is given in Fig. 190 and the operation is as follows:

The two electromagnets A and B are arranged to attract the iron armature C pivoted at D, which closes contacts E
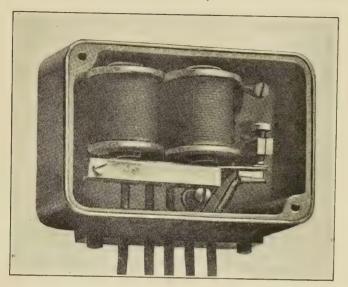
Fig. 189.—Bell-ringing relay for circuit breakers.
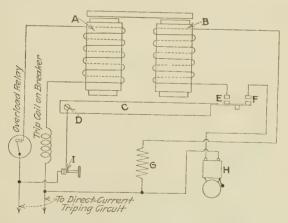
Fig. 190.—Diagram of connection for bell-ringing relay.

and F when attracted. The solenoid A is placed in series with the trip coil and relay contacts of the breaker, so that when the

relay closes it energizes solenoid A. This attracts armature C
and closes both contacts E and F. Contact E closes the circuit
to solenoid B through a resistance G, and contact F closes the
circuit to a bell or alarm H. Now, even though the circuit
to A is opened, as it would be if the breaker opened, solenoid
B still holds the contacts closed and the bell will continue to
ring until the switch I is opened for an instant, which allows the
armature to drop and the contacts to open. These relays
can be used when a direct-current circuit is available for tripping
the breaker. It will also be seen that should the breaker be
tripped by hand, the relay cannot operate, consequently
the bell rings only on automatic tripping.

Temperature Relays.—When large power units are used
in generating and transforming electric energy, some means
must be employed to keep the windings cool when they are
heavily loaded, as the capacity of a machine is limited largely
by the maximum temperature which the insulation will stand.
From this it follows that if apparatus is installed to remove
the excess heat and keep the temperature within allowable
limits, then a given machine will have a greater capacity than
one in which no such cooling devices have been employed.

There are several methods of cooling electric machines. The
simplest is by immersing the whole machine in a tank of oil
(as in the case of an oil-cooled transformer) where the heated
oil rises to the top, cools off and sinks again to carry away
more heat. The cooling of the oil is sometimes hastened
by installing coils of pipes in the top of the oil and pumping
cold water through the pipes.

It is obvious that these methods cannot be used for genera-
tors or motors, so cold air is resorted to, large motor-operated
blowers forcing the air through suitable ducts or channels in
the iron and windings.

In a few instances, the light-load losses have been so low
that there is no necessity for operating the blower motors
when the machine is unloaded. Neither is it necessary to start
them for a short-time heavy load. It is when the units get
hot that the blowers must start. For this purpose temperature
relays may be used. They start the blower motors when the
protected apparatus reaches a certain high temperature and

continue blowing until the apparatus is cooled down to a certain degree. In other cases, the relays are used to trip out the breaker, or to ring a signal bell informing the attendant that the machine is too hot and needs a revision of load or another unit cut in service. Sometimes even this cutting in of a new unit is done automatically when the temperature reaches a certain limit and the extra machine cut out when the temperature goes down. The great advantage of temperature relays over overload relays is that a motor or generator can be held in until it gets hot enough to start actual deterioration of the insulation.

D.C. Temperature Relays.—To accomplish this control without the use of thermometers or any other time-old methods of measuring temperature, advantage is taken of the fact that the resistance of copper wire varies with the temperature. Then a Wheatstone's bridge arrangement is used with a sensitive direct-current relay instead of a galvanometer; the
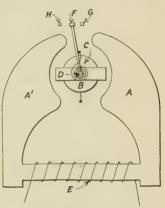
Fig. 191.—Internal diagram of D.C. temperature relay.

copper wire is wound on a card and placed in a spot in the transformer or protected apparatus where the hottest, or rather indicative, temperature is liable to be, and when its resistance reaches a certain amount, the relay closes its contacts by unbalancing the bridge. The copper-wound card is called the exploring coil.

The principle of operation of the D'Arsonval type is shown in Fig. 191. The main casting A-A' has an iron core B producing an annular gap C in which the moving coil D turns on jewelled bearings. The magnet A-A' is magnetized by the coil E, which, in practice, is connected directly across the line or potential. The moving coil D has a contact F which touches G when it moves one way and H when it moves the other.

Figure 192 shows the diagram of connections. A, A' and A'' are resistance units wound with wire having a zero temperature

coefficient and are each equal to resistance of the copper wire exploring coil *B* at its normal temperature. The four resistors are connected in bridge arrangements, the potential being supplied at 1 and 2 and the moving coil (in place of galvanometer) at 3 and 4.
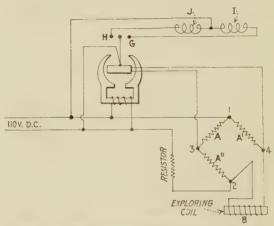
Fig. 192.—External diagram of connections of D.C. temperature relay.

For a moment, consider Figs. 193 *a*, *b* and *c*. In the first, Fig. 193*a*, the resistance of the exploring coil is less than the other three so current flows from left to right. Then, as it gradually gets warmer, its resistance increases until it
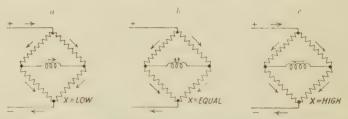
Fig. 193.—Showing the direction of current in the "moving-coil" circuit.

becomes equal, when no current flows (Fig. 193*b*). A further increase in resistance (temperature) causes the current to reverse, and the higher the resistance, the greater the current in the moving coil.

Now returning to Fig. 192, it will be seen readily that if the

current causes the coil to turn to the right, then when it reaches a certain amount, the contacts *G* will close. This completes the circuit to the closing coil *I* which closes a breaker and starts the motors blowing, or rings a bell, etc. When the breaker closes, auxiliary contacts open the circuit to relieve the relay contacts. The apparatus gradually gets cooler and the resistance of the copper wire exploring coil which is wound in the machine decreases until the current in the moving coil has reversed to such an extent that contact *H* is closed. This completes the circuit to the trip coil *J* and the breaker opens.

If the voltage of the D.C. circuit varies, it will affect the accuracy somewhat, but this error is extremely small at the balancing or reversing point, consequently this is the point generally chosen at which the relay closes its contacts on high temperature. While this arrangement may be used to protect either A.C. or D.C. apparatus, it requires a constant D.C. source for its operation.

A.C. Temperature Relays.—When it is desirable to have the relay trip out the circuit in the event of excessive temperature, the A.C. temperature relay is generally used as it may be arranged to trip out the circuit on high temperature, but only if the excessive current is still flowing. For instance, say it is a generator that is being protected. The exploring coil would be wound and imbedded in the stationary part and consequently attain the same temperature as the part in which it is imbedded. Due to a quick, heavy load, one portion of the machine may attain a quite high temperature, but before this temperature can reach the search coil, the load may decrease. But the heat, in dissipating from the hottest part, may still continue to raise the temperature of the cooler parts, and then in a short time the search coil may get hot enough to trip the relay. Still, there being very light load, the machine, as a whole is actually cooling and will continue to cool.

This shows the necessity of using a relay that will not trip when the temperature is high unless there is also a heavy load; nor will it trip on a high load unless the temperature is high.

It takes *both* high temperature and high load to operate the relay. The connections, internal and external, of this relay are shown in Fig. 194. This shows the regular induction-type

element A with disk B arranged in the regular manner, so that movement of the disk closes the contacts C. It will be noticed that the current transformer supplies two circuits; one excites the main coil of the relay and the other furnishes potential to the bridge arrangement. This bridge arrangement consists of two unchanging arms D and E (usually placed inside the
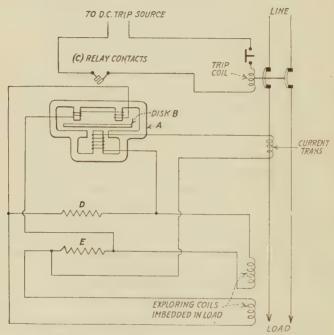
FIG. 194.—Connection diagram of A.C. temperature relay.

relay) and two search coils imbedded in the winding of the generator or transformer being protected.

The other actuating winding of the relay (on the two poles) is used in place of the galvanometer. Since the torque on the disk is the *reaction* or the multiplication of the currents in the two windings, it is very evident that even though there is a heavy current flowing in the main coil, it will not trip if there is no current in the other two poles (due to unbalance of bridge); neither can the relay act if the search coils get hot enough to

unbalance the bridge and force current through the two poles unless there is a current flowing in the main coil.

This shows that the only condition that will trip the relay is excess temperature and heavy current.

Temperature relays may seem like an added expense and luxury to the average power plant, but a careful survey of the situation may reveal certain conditions which, by their elimination, will soon pay for an installation of good relays. For instance, note how many hours the generator or transformer is operating at light load with the blower motors working at full capacity. Note how much power they take and the saving that could be made by automatically stopping the blowers when they are not required. The cost of burnt-out units might also be classed as a case where temperature relays will effect a great saving, as there are many cases where the relays will give a signal that the apparatus is approaching a dangerous temperature, thus enabling the attendant to act quickly and distribute the load so that the machine in question is relieved. Of course temperature relays are not an absolute guarantee against burnouts, as unavoidable accidents are always liable to occur; but if the relays will prevent even one burnout which might occur were the relays not installed, then they will have paid for themselves both in monetary value and satisfaction of operation of the power plant.

RELAY SWITCHES

In all the relays so far, we have assumed that the contacts themselves closed the circuit to the trip coil of the breaker, but when the breakers are large and require considerable current to trip them, the contacts of the delicately constructed relays are not heavy enough safely to close the heavy current required. To overcome this difficulty, a relay switch as shown in Fig. 195 is used. This switch consists of a solenoid S with an iron plunger P, to the bottom of which is attached a loosely held carbon disk C, insulated from the metallic plunger. When the overload or the definite-time-limit relay closes its contacts, it closes the circuit to the relay switch, and the energized solenoid instantly pulls its plunger upward, thereby pressing the carbon
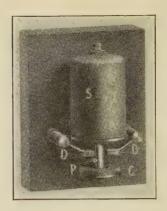
Fig. 195.—Relay switch with carbon contacts.
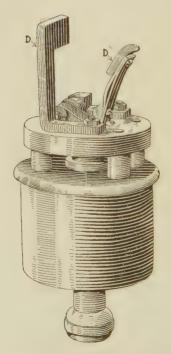
Fig. 196.—Relay switch with contacts at top.

disk *C* against the two stationary carbon contacts *D* and *D*. Short-circuiting these contacts closes the circuit of the shunt-trip coil on the circuit breaker. The contacts being of carbon will carry a heavy current and will not stick. In another form of relay switch, Fig. 196, the plunger simply pushes up a pivoted arm, thus closing the two contacts *D* and *D*.
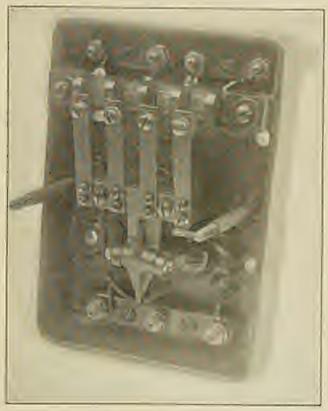
Fig. 197.—Westinghouse multi-contact relay.

Sometimes it is desirable to trip two or more breakers at once with the same relay switch. In this case the disk is generally made of copper, and two or three sets of stationary contacts are used, thus closing two or three circuits simultaneously. Another multi-contact relay is shown in Fig. 197.

It must be remembered that the arcing at the relay contacts will always be a great deal more severe when opening a circuit than when closing one. For this reason a relay should never open the trip circuit once established. If the trip circuit is fed from the load side of the breaker, it will be opened automatically when the breaker opens and the circuit will be dead when the relays reset. Should it be necessary to connect the shunt
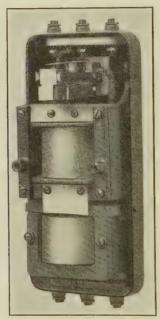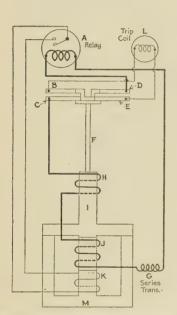
Fig. 198.—Westinghouse "transfer" relay.

trip circuit to the line side of the breaker, or if a separate circuit is used, then a switch must be arranged to open the trip circuit as soon as the breaker opens, thus relieving the relay contacts of this duty.

Transfer Relays.—To prevent the failure of trip circuits as well as to apply relays where a direct current is not available, series-trip or circuit-opening relays may be used, but their inherent fault of opening a breaker on slight vibration has discouraged their use. However, by using a "transfer relay," as it is called, the advantage of the series-trip relay may

be obtained without its drawback. Figure 198 shows one of these relays and Figs. 199 and 200 a diagrammatic scheme of parts. *A* is a standard circuit-closing relay. The contacts on the upper end of the shaft *F* are arranged so that *C* makes contact with *D*, while *E* makes contact with *B*, in normal position, Fig. 199. When the plunger is pulled up *C* makes contact with *B*, while *E* makes contact with *D*, Fig. 200.

Fig. 199.—Internal wiring diagram of transfer relay.

Fig. 200.—Showing positions of core and switch after tripping.

The current from the series transformer *G* passes through the relay *A* and through two coils in the transfer relay. Coil *H* tends to raise the plunger *I* but coil *J* tends to hold it down, and since the current in both coils is equal, the plunger will not be moved.

Wound on the same core with coil *J* is another coil *K* with its terminals connected to the relay contacts. When the relay contacts close they short-circuit coil *K*, which has set up in it a current by the transformer action of coil *J*. This current being

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in opposition to the current in coil J tends to demagnetize the core M and it loses its attraction for the plunger I, allowing coil H to pull it up. This changes the switch at the top to the position shown in Fig. 200. It will now be noted that the current is flowing through the trip coil L, which will trip the breaker.
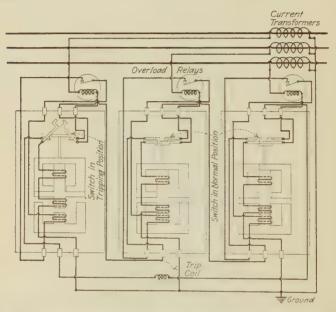
FIG. 201.—Diagram of transfer relay connected on three-phase circuit. Left-hand relay tripped.

Figure 201 shows three single-phase relays protecting a three-phase line in connection with three transfer relays. When the plungers are all down, the trip coil is entirely insulated from the series circuit. If any one, two or three relays operate, they will complete a circuit through the trip coil and current transformers under any conditions that may arise. The overload relay A gives the necessary accuracy, while the transfer relay gives the advantage of a series-trip or circuit opening system.

High-tension Relays.—In using an overload relay on a high-tension circuit, it has generally been customary to use high-

tension current transformers, which, of course, thoroughly insulate the relay circuit from the high-tension primary and allow the relay to be placed on the board. When the current is over 100 amp. it requires only one turn (*i.e.*, a straight wire) in the primary and consequently the insulation of the primary becomes a comparatively easy matter. Current transformers of one turn are often built right around the terminal bushings of a circuit breaker, using the terminal rod itself as the primary.

When the current becomes less than 100 amp., the primary must consist of more than one turn, and the insulation becomes a difficult matter, especially on an extra high-tension circuit, as for instance a 66,000-v. or a 110,000-v. line.

To overcome this, the complete relay such as the plunger-type may be mounted on a pillar insulator, and connected directly in the high-tension line. Then if the plunger is attached upward, due to overload, it pulls the long, insulated chain, which mechanically operates a set of trip contacts, thus closing the trip circuit to the breaker. This chain is made out of micarta links, the number varying according to the potential.
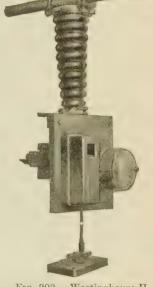
Fig. 202.—Westinghouse H. T. current relay mounted on post insulator.

A 44,000-v. circuit should be supplied with 12 links on account of surges; a 66,000 with 20 links and a 110,000 with 30 links. This allows the solenoid to be mounted on a disconnecting switch or other insulated support and the trip contacts to be in the most convenient location.

Westinghouse High-tension-relay Combination.—Realizing the great advantage of an accurate high-tension relay, and the inability to secure accuracy with a solenoid type, the high-tension induction and transfer relay shown in Fig. 202 was developed. It consists of the accurate induction-type relay (previously described) and a transfer relay mounted on

a small panel, which in turn is mounted on a pillar insulator. Instead of the transfer-relay plunger operating the switch, it merely pulls the micarta chain, which closes the low-tension trip-circuit contacts.

The induction relay retains all its inherent characteristics of inverse, definite-minimum time, its selective action, permanence of accuracy, etc., and the transfer relay adds the positive tripping motion, using the A.C. current energy for operation and not depending on an auxiliary trip circuit. Together, they form an unexcelled protective relay for high-tension circuits, being readily adapted to simple circuits, radial systems and parallel feeders.

TIMING RELAYS WITH A CYCLE COUNTER
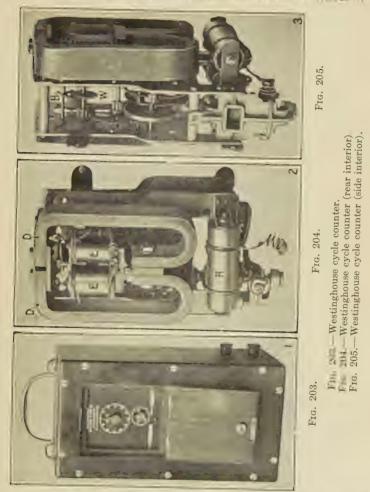
Before the introduction of the cycle counter, the generally approved method of determining the time delay of a protective relay was to use a "stop watch" or chronometer, starting the watch simultaneously with the application of overload and stopping it at the instant of tripping. With the older relays, having a time delay of several seconds, this method gave satisfactory results, but with the present-day relays, designed with watt-hour meter accuracy and capable of being set within fractions of a second, it is obvious that the stop-watch method is not at all suitable.

A stop watch at best cannot be relied upon closer than about $\frac{1}{5}$ sec., and when to this is added the personal error of starting and stopping, it gives a possible error almost as great as the time between various sectionalizing relays. It is not at all unusual to set sectionalizing relays in a radial system only $\frac{1}{2}$ sec. apart, and in some cases good results have been obtained with relays set only $\frac{1}{8}$ sec. apart.

To measure the time delay of a protective relay accurately and automatically is the function of the cycle counter. This instrument is shown in Fig. 203, while two interior views are shown in Figs. 204 and 205.

Principle of Operation.—The cycle counter consists essentially of a self-winding clock in which the escapement wheel or pendulum is replaced by a polarized relay. The diagram-

matic scheme of parts is shown in Fig. 206. The regular escapement wheel is shown at W. Attached to this is the indicating pointer moving over a suitable scale (as shown in Fig. 203). The escapement bar B allows the wheel W to

FIG. 203.

FIG. 204.

FIG. 205.

Fig. 203.— Westinghouse cycle counter.
Fig. 204.— Westinghouse cycle counter (rear interior).
Fig. 205.— Westinghouse cycle counter (side interior).

escape one tooth per oscillation in the regular manner. Rigidly attached to the bar B is an iron armature, polarized by the permanent magnets D and D'. Part of the magnetic circuit is formed by the two electromagnets E and E', which are capable

of attracting and repelling opposite ends of the armature. The action is as follows:

Assume that during the first cycle of applied current, the
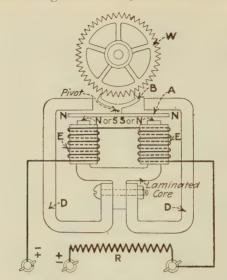
FIG. 206.—Schematic diagram of cycle counter.
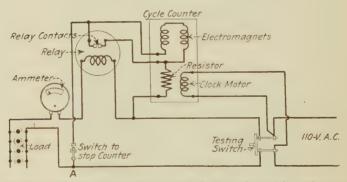
FIG. 207.—Connections for testing circuit-closing relay with cycle counter.

current flows from the $\pm$ to the $\mp$ terminal. This will produce an N-pole on the armature end of the right-hand electromagnet and an S-pole on the corresponding end of the left-hand electro-magnet. As both ends of the armature are polarized N the right-hand end will be repelled and the left-hand end attracted.

During the second half of the cycle, the current is reversed, and now the right-hand end is attracted and the left-hand end repelled, which naturally results in one oscillation of the bar *B* and the escapement of one tooth. From this it will readily be seen that the wheel moves one tooth per cycle as long as the electromagnets are energized. A small electric motor, controlled automatically, re-winds the main clock spring, when it has unwound a certain amount. This keeps an even tension on the escapement, and the electromagnets are thus not depended on to drive the mechanism, but simply to regulate its speed.

Timing a Circuit-closing Relay.—Determining the time delay now becomes a problem of energizing the electromagnets
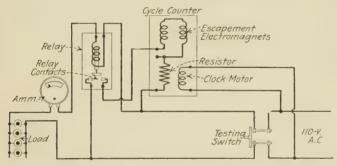
Fig. 208.—Connections for testing circuit opening relay with cycle counter.

simultaneously with the application of load and de-energizing them upon the instant of tripping. This is most easily done by temporarily disconnecting the relay from the circuit and connecting to a test circuit with connections as shown in Fig. 207, using a lamp bank or other suitable resistance for the load and a switch by which this load may be quickly applied. While adjusting the load, it is best to disconnect the lead at *A* to avoid unnecessary wear on the counter. Another switch may be provided for this purpose if desired. After adjusting the load, the main-testing switch is opened, the relay allowed to reset fully, and the cycle counter pointers set on zero. Then the switch is closed, thus applying load and potential to the relay and counter. The counter revolves, one tooth per

cycle, until the relay contacts close, when they short-circuit the escapement electromagnets and thus stop the counter instantly.

The number of cycles indicated, divided by the normal frequency of the testing circuit, will give the time delay in seconds. For instance, if used on a 25-cycle circuit and the counter indicates 50 cycles, the time will be 2 sec.; if on a 30-cycle circuit, then the time will be $1\frac{2}{3}$ sec., and so on.

A number of operating companies do not reduce the cycles to seconds, but the testing reports and curves give the time delay directly in cycles, thus affording units which are more easily handled than fractions of a second.

Timing a Circuit-opening Relay.—In determining the time delay of a circuit-opening relay, it is simply necessary to connect the escapement solenoids in series with the relay contacts as shown in Fig. 208. Closing the main testing switch energizes both relay and counter simultaneously and the counter stops the instant the contacts open.
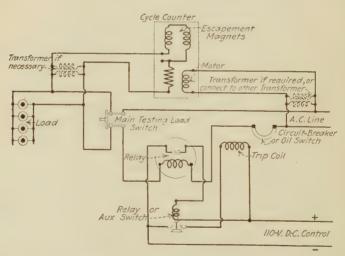
Fig. 209.—Connections for testing complete protective equipment.

Timing the Breaker or Oil Switch.—Realizing that it is necessary to make allowance for the time taken by the breaker or oil switch and its auxiliary equipment to open the circuit, it is sometimes preferable, in a closely set system, to time the

whole combination as a unit. To do this, a load must be arranged so that it can be thrown quickly directly on the line, with connections similar to those indicated in Fig. 209.

The counter is connected to the load side of the switch. It is energized at the same instant that the load is applied and is de-energized the instant the breaker or switch opens.

This not only gives the time delay between instant of overload and opening of circuit, accurately and automatically, but also insures that all protective apparatus is functioning properly.

Typical Layout.—In Fig. 210 is shown a typical layout which may be used to illustrate the uses of the different kinds of relays.

There are six generators shown which feed through individual switches to the low-tension bus. Each generator is protected by relays shown at 1 which may be overload, definite limit relays of the plunger or induction type, or reverse-power relays with current setting slightly less than the sustained short-circuit current of the generators; or they may be differentially-connected overload relays, connected to trip the breaker instantly in case of a fault in the winding.

The bus is arranged to sectionalize in three sections, so if any bus section becomes defective, the overload relays 2, which should be of the instantaneous plunger or induction type, will instantly sectionalize the bus.

The low-tension bus is arranged to feed four step-up transformers (on the left) and a low-tension radial system (on the right). Each step-up transformer bank is protected by instantaneous, differentially-connected overload relays 4. These trip out an individual bank in case of internal trouble. The transformers are protected from overload by the inverse-definite minimum-time-limit relays of the induction type shown at 3. The high-tension bus is also capable of being sectionalized by the instantaneous overload relay 2. From this bus, transmission lines run to two substations *A* and *B*. Each station is fed with two parallel feeders, protected at the generating end by overload, inverse-definite minimum-time-limit relays 5 and at the receiving end by reverse-overload relays 6 and 7. Between the two stations is run another line, making

a ring system. This tie feeder is protected by reverse-overload relays.

Relays 3 should be set for about 2 sec.; relays 5 for 1½ sec.; relays 6 and 7 for 0.5 sec.; and relays 8 for 1 sec.
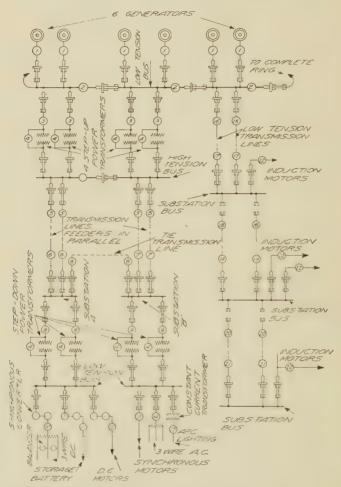
Fig. 210.—Indicating the use of relays on typical power station.

The high tension is stepped down by two transformers at *A*. These are protected by instantaneous, differentially-connected relays 4 and overload relays 9 set low about 1 sec. The

low-tension bus feeds three rotary converters, which feed a three-wire direct-current system, a storage battery and a direct-current motor load. Relay 10 may be an overload relay with under-voltage and over-voltage auxiliary relays. Relay 11 should be a high-grade reverse-current relay. Over-voltage, overload, underload and under-voltage relays may also be used. Relay 12 should be an overload relay set about ½ sec. or instantaneous.

At substation *B* the high tension is stepped down and protected as before. This secondary bus may feed a load of synchronous motors, a three-wire alternating-current system and a constant-current lighting circuit. Relays 13 may be overload or reverse phase. Relays 14 should be overload with additional under-voltage and over-voltage relays. Relay 15 should be an underload relay.

From the main station is run a radial system of parallel feeders. Relays 17, 19 and 21 are reverse-power relays, set about 0.1 sec.; relays 16, 18 and 20 are accurate overload inverse, definite-minimum relays of the induction type. Relays 16 are set for 1½ sec.; 18 for 1 sec.; and 20 for ½ sec. At each substation bus are taken off a various number of loads, and each is protected by relays which may be of the plunger type as long as they operate in quicker time than the protecting sectionalizing relays.

It is evident that no one layout will suffice for all systems; neither can invariable rules be laid out for the use of any relay. It becomes a study of each individual system, but with a knowledge of the various loads, and how they divide in the event of short-circuits, together with the knowledge of the maximum currents, it becomes comparatively easy to apply relays and set them to give adequate protection and reduce unintentional interruptions to an almost negligible quantity.

CHAPTER XV

TESTING DIRECT-CURRENT RELAYS

No matter how carefully a relay is constructed or tested, it is always well to remember that no piece of apparatus is infallible. For this reason, all relays should be tested before installing, and should be subjected to periodic tests after installation.

In well-equipped meter shops will be found adequate apparatus such as meters, leads and batteries for making simple or elaborate tests, as the case may be. This chapter will, therefore, treat mainly of tests made on the relays while in service.

Installing.—Practically every manufacturer gives complete and elaborate directions for the installation of his particular type of relay, and these instructions, of course, should be carefully followed to obtain correct results. In general, they deal with mechanical features such as seeing that the moving parts are free; that there is no dirt or packing material in the relay; and that there are no loose screws or nuts or damaged parts. A diagram of connections also accompanies each relay and this should always be used in the absence of another authoritative diagram, which might be used to include other instruments in the same circuit. A relay should always be mounted on a firm, solid support such as a switchboard. It must be accessible for easy inspection and testing, and never mounted in a place where it will be subjected to excesses in temperature, moisture, destructive fumes or stray fields. In case a relay must be installed in a dusty place, for instance, a flour mill or cement mill, it must never have open contacts; they must always be enclosed; preferably in a glass cover. If a cover does not accompany the relay, the relay should be enclosed in a glass-covered dust-proof box.

The circuit breakers and switches, too, must receive periodic attention in order that they should not fail at a critical moment. In fact, manufacturers sometimes recommend that the whole

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protective combination of relays, relay switches and circuit breakers or automatic oil switches be used to open the circuit whenever it is absolutely necessary to open it, thereby insuring correct functioning of all units.

Ground Testing.—Before installing and before making a periodic test, the relay should be tested for "grounds." While this is really a test for live metal-to-frame defects, it will readily detect defective spots in the insulation which must be reinsulated against all possibility of breakdown in service. Figure 211 shows the development of the winding of a standard ground-
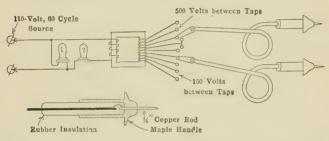
Fig. 211.—Small potential transformer fitted with dial switch and insulated leads for testing purposes. Lamp 1 indicates that the circuit is alive, lamp 2 lights only on a ground between testing terminals.

test outfit capable of giving from 0 to 2,000 v. in 100-v. steps. It is merely a small step-up transformer arranged with a primary to connect to 110-v. A.C. and a secondary with taps. There are four taps with 500 v. between adjacent taps, and six taps with 100 v. between taps; by connecting to a suitable dial switch, any voltage in 100-v. steps is obtained. In the primary is connected a snap switch and lamp. As a ground is equivalent to a short-circuit in this test, it will light the lamp, thus indicating the defect. The other lamp merely tells if the transformer primary is energized. In the cover there is also a spring switch, so if the cover of the box is opened, as is necessary in order to change the dial switch, the primary circuit is immediately opened, thus preventing possible personal damage by accidental contact with the live, high-voltage secondary.

The test voltage used for the current winding should be about twice the normal voltage of the circuit to which the relay is

connected, plus 1,000 v. When a separate trip is used, the live
parts of the trip circuit should be tested for grounds. A test
should also be made between the coil circuit and trip circuit
terminals. Figure 212 shows the method of procedure. One
lead is held on the frame, preferably on an unenamelled screw
head, and the other is touched to terminal A and B. If nothing
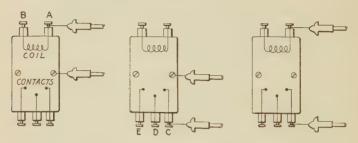
Fig. 212.—Ground-testing a bellows type relay.

happens, the lead is then touched to trip terminals C, D and E.
If this shows intact insulation, touch one lead to terminal A
and one lead to C, D and E in succession. If a dead metal-to-
metal connection is present, lamp 2 (Fig. 211) will light; other-
wise nothing will happen. If due to insufficient insulation,
the ground will often show up by a slight arc or smoke. The
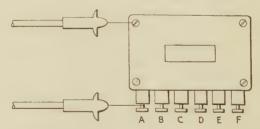
Fig. 213.—Ground-testing a D'Arsonval type relay.

relay cover should always be on during ground tests, and often
it is advisable to test first with the contacts open and then
again with them closed.

Figure 213 shows how to test a moving coil D'Arsonval
type relay. In this there are three separate circuits, so it is

necessary to test between each circuit and frame, and from each circuit to the others. If A and F; B and E; and C and D, are circuit terminals, first touch one lead to the case, and one lead to A, B, C, D, E and F in succession; then touch one lead to A and one lead to B, C, D and E in succession; then one lead to B and one lead to C and D.

Testing Relay Switches.—The relay switch is perhaps the easiest piece of protective apparatus to test. First make sure that all screws and nuts are tight; that it is firmly mounted; no loose connections; and that the contacts (if metal) are clean and bright, and not burnt.

If they are burnt or pitted, take a piece of fine emery cloth (never use crocus paper, it leaves a muddy deposit) and, doubling it, work it back and forth between the contacts, which should be held firmly against the emery. In this way, grind the surfaces until they meet accurately.

Then energize the solenoid by connecting to a circuit of the correct voltage and see that the plunger rises freely and quickly and closes the contacts positively and firmly. If the trip circuit is operated from a storage battery, it is well to see that the plunger rises satisfactorily when the solenoid is energized on 70 per cent and 130 per cent of the normal voltage. This is to insure correct operation no matter how low or high the battery voltage may go. Failure to operate should be carefully investigated and the cause removed. It may be due to foreign substances, bent parts or rubbing magnetic surfaces.

Various Testing Loads.—If a D.C. circuit is available, and the relay to be tested is of the millivolt type, a portable lamp bank or a load box as shown in Fig. 214 may be used with connections as shown in Fig. 215. If undesirable to trip the breaker in making the test, substitute a lamp as shown.

Loads for Series-type Relays.—The series-type, such as the plunger, relays are not so convenient to test, as the whole load must be passed through the series coil. If at all possible, this is done by building up the load until the breaker trips.

This test can often be made at night when an occasional interruption does not harm the service. If the load is large, water rheostats may be used. A large barrel, filled with water, with an electrode at the top and bottom will handle consider-

able load. The variation is obtained by continually adding salt, meanwhile watching the ammeter and noting the point at which the relay trips. As an illustration of how great a
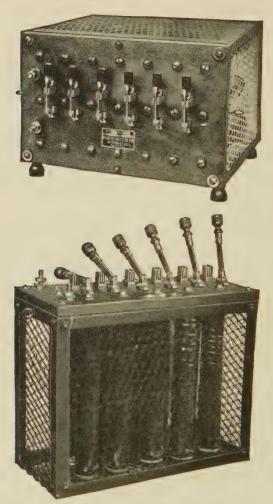
Fig. 214.—Typical resistance load boxes.

current may be controlled in this manner, a barrel 3 ft. deep with electrodes 2 ft. square should handle 500 amp. easily at 100 v.

Another way of obtaining a load is to immerse an iron-wire rheostat of the necessary resistance in running water.

For smaller loads, and where it is undesirable to interrupt
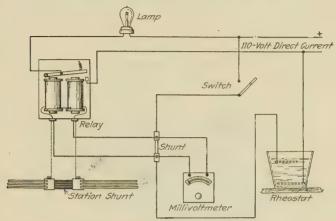
Fɪɢ. 215.—Testing relay with a separate source.

Fɪɢ. 216.—Typical portable storage battery. (Elec. Storage Battery Co.)

the load, a storage battery such as shown in Fig. 216 may be used with a water rheostat or a carbon rheostat. A good home-made carbon rheostat is a wooden box filled with arc-lamp carbons and brass plates. The handle can be screwed

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in, compressing the carbons and plates and lowering the resistance, thus increasing the current.

A box 12 in. long by 6 in. wide by 6 in. deep should carry 20 amp. continuously at 4 v. and will regulate as high as 200 amp. for short intervals of time. The regulation is made in infinitely small steps.

Leads with heavy spring clips on the ends will be found very convenient for making quick connections and will carry several hundred amperes. An excellent make of clip is shown in Fig. 217.
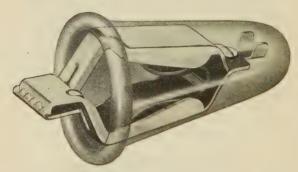
FIG. 217.—"Big Brute" testing clip. (Mueller Elec. Co.)

Testing a Millivolt-type Relay.—Say for example a millivolt-type relay must trip when the load reaches 800 amp. but it is impracticable to get this load. First disconnect the leads *at the shunt*, and the trip leads at the relay. Give the usual mechanical inspection, clean the contacts and ground test. Note the capacity of the shunt; say it is 50 m.v. at 1,000 amp.; therefore, at 800 amp. it would give 40 m.v. (1,000 : 50 = 800 : x). Instead of saying that the relay must trip at 800 amp. we can say that it must trip on 40 m.v.; then it simply becomes a problem to obtain 40 m.v. from an external source. Take a standard shunt giving 50 m.v. at 5 amp. and connect in series with the testing load. Gradually increase the load until the millivoltmeter reads 40 m.v. and adjust the relay so it trips. Several trials may be necessary. Note that the current is unknown exactly but that it takes approximately 4 amp. in the shunt to produce exactly the same effect on the relay as 800 amp. in the station shunt. Then, reconnecting the relay to the

station shunt, we know it will trip on 800 amp. although we
only tested it with a 4-amp. load.

Testing Plunger-type, Instantaneous-trip Relays.—Give the
relay a thorough mechanical inspection, carefully trying every
nut and screw and looking for burnt coils and loose con-
nections; clean the contacts and then ground-test. If the
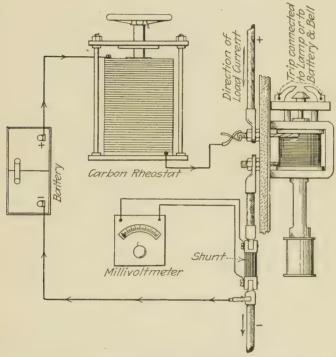
FIG. 218.—Connections to boost or buck the station load.

current capacity is low, say, below 25 amp., it may be pref-
erable to connect a jumper around the relay to complete the
circuit and then disconnect the relay from the circuit, recon-
necting it to the test load. If of a larger capacity, it is preferable
to build up the load on the circuit itself, if this can be done
without interfering with the service. Otherwise, connect
a storage battery and rheostat as shown in Fig. 218,
being sure to include the station shunt in the battery circuit.

This enables the main-load current to be used in addition to the test current; or if the load current is already too high for the lower settings, reverse the battery and buck the load current down.

For instance, if a relay must trip on 600 amp. and the load current is only 500 amp., then the battery must supply the extra 100 amp. It is not necessary to measure these separately, but the station ammeter will read their sum.

Testing Time-limit Relays.—After making all connections so the load, or overload, can be quickly applied, the time may be determined with a stop watch. First carefully set the rheostat to give the desired current, at which current it is desired to take the time; disconnect and let it fully reset. Then quickly apply the load and press the crown to start the watch; both at the same instant. Press again to stop the watch when the contacts close. The watch hand indicates in fifths of a second the time required to close at that particular current. A third press resets the watch for the next trial.

If impossible to apply the load quickly, quite close results can sometimes be obtained by building up the load and holding down the plunger by hand, releasing it and snapping the watch at the same instant.

By varying the load and the time settings, the time of the various combinations can be obtained.

CURVES AND TABLES

Whenever relays are tested, the results of the test should be permanently recorded in curves or tables. On relays without time-delay element, the actual amperes may be plotted against the setting as in Fig. 219. To do this, set the relay for the lowest setting (say 4 amp.); then slowly raise the current and note the reading of the ammeter just as the plunger rises.

Say it takes 4 amp. Make a dot where the 4-amp. horizontal and vertical lines intersect. Change the setting to 5; then it may take only 4.75 amp. So make a point where the 4.75 horizontal line intersects the 5 vertical. In the same way locate the currents required for 6, 7 and 8 amp., and draw a curve through them.

Now suppose a relay is set for 4 amp. and gives satisfactory service. Then, for some reason, it is desired to have the relay changed to 8 amp. Before changing to the No. 8 setting, the operator would look up his curve and see that the relay took only 7.5 amp. at this setting. This might be satisfactory or it might be necessary to readjust the relay to give 100 per cent accuracy at this point. In any case, the curve has saved
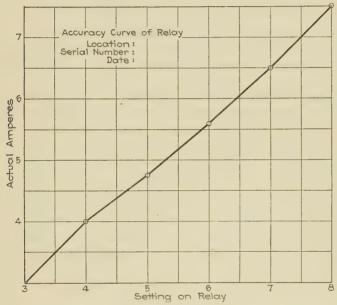
Fig. 219.—Accuracy curve of relay.

the operator from depending on the relay to trip at 8 amp. and distributing his load accordingly, only to have it trip at 7.5 amp., perhaps throwing out the whole system without cause.

Time limit relays require more elaborate curves and tables. It is generally best to plot the load on a certain setting against the time. This requires a separate curve for each setting, although these are frequently made on the same sheet.

Curves are generally to be preferred to tables when in intelligent hands, but there is less liability to error in using tables and expert opinion is divided as to which is preferable.

CONCLUSION

In making very accurate tests, in which the trip circuit has been disconnected, time must be allowed for the closing of the relay switch and opening of breaker. In general this will be found to be 0.2 or 0.3 sec., so when setting the relays for actual operation, it must be remembered that the breaker does not actually open until 0.2 or 0.3 sec. after the contacts close.

In setting time accurately, the type of relay must be considered and its limitations taken into account. This is especially true of the bellows and dashpot relays. The bellows, unless carefully oiled every few months, will harden and the time of trippings cannot be depended upon at all. The dashpot relays will give greatly-varying time due to a change in the viscosity of the oil if used where they are subjected to extremes in temperature. The oil supplied by the maker should be used to the exclusion of all others.

When making tests, it must be constantly borne in mind that the circuit is left without protection, and great caution must be used that an overload does not occur in the interval of testing. Some modern boards have their relays arranged with testing switches which automatically disconnect a relay but connect in a spare relay for protection during test. But even in this case, too much caution cannot be used to insure against material damage, personal injury and avoidable interruptions.

CHAPTER XVI

TESTING ALTERNATING-CURRENT RELAYS

Since protective relays use the same principles of operation as are used in indicating instruments, it follows that they will require the same classes of instruments and apparatus to test them. For testing purposes, the relays may be divided into three classes: Those requiring current alone for their operation; those requiring voltage alone; and those requiring both current and voltage. Since the majority of relays operate on current alone, this class will be considered first.

Relays, like every other piece of mechanical apparatus, are prone to develop inaccuracies and irregularities; consequently a comprehensive periodic system of testing should be developed and rigidly followed out. Some companies make it a practice to test relays every six months; others test after every disturbance which causes the relays to operate. This practice is often necessary on the bellows-type relays, but is questionable for the induction type.

RELAYS REQUIRING CURRENT ONLY

When considering the testing of current relays, there are five main points to be considered. First, the source of testing supply; second, the load and its regulation; third, the measuring instruments; fourth, the trip circuit; fifth, the measurement of the relay time of operation.

If possible, there is only one correct way to test a relay, and that is, to make a dead short-circuit on the protected apparatus and see if the relay operates and opens the breaker. However, this is seldom possible or desirable, as it not only throws a heavy strain on all the apparatus, including the generators, but entails a momentary interruption to the service. However, an occasional accidental "short" which is properly cleared

is the best assurance that the protective apparatus as a whole is functioning properly.

The Source.—Instead of waiting for the accidental short-circuit to occur, it is customary to subject the relays and auxiliary apparatus to periodic tests which indicate that they are in condition to clear actual trouble. Thus, in testing, the relays are disconnected from the circuit, and current supplied from an independent source. The trip is also disconnected from the circuit breaker, and a signal lamp or cycle counter connected in to determine the time. Since the independent source of testing supply need only supply the losses of the relay, and these losses amount to only a few watts (100 at the most), it is customary to use the ordinary lighting circuit as the source. Oftentimes, when there are a large number of relays in one location to be tested, a line or source is conveniently supplied. Of course, the source must be the same frequency as the normal frequency upon which the relay works and it must first be ascertained that the lighting circuit is not fed from a storage battery or spare unit, as is often the case, in order to provide an unfailing source of light in case all other apparatus fails.

The Load.—The relay itself must now be considered. It may be of the series type, in which case the winding is generally heavy, often being of heavy copper strap, wound on edge, and in many cases, a single bar passing through the relay. This is known as the primary type. Or it may be wound to operate from the secondary of a series transformer. This is known as the secondary type and the standard practice is to use approximately 5 amp. for its operation. Loading up a primary relay sometimes becomes a difficult matter, especially in the larger size, but loading a secondary relay becomes a very simple matter. As a 5-amp. relay requires only a few volts to force the necessary current through it, an additional current-limiting resistance or reactance is generally used in series, if the current is to be taken from a 110-v. circuit. This may be a lamp bank, a resistance unit, a resistance or load box, or a choke coil, or reactance or impedance coil.

Reactances are seldom used, as the wave form of their currents is liable to be peaked, and while present-day relays are but slightly affected by distorted wave forms, it is undesirable to

introduce any possible source of error. Resistance or load boxes are often used. These are arranged with a number of resistance coils. All the coils are connected together on one side but the other ends pass through individual switches, which allow any number of coils to be placed in parallel. The coils have various resistances, so that each switch allows a certain amount of current to flow. For instance, when all connections are made,

FIG. 220.—Ward Leonard resistance unit.

and switch No. 1 is closed, it allows $\frac{1}{2}$ amp. to flow through the circuit. Now if switch No. 1 is opened and switch No. 2 closed, it may allow 1 amp. to flow. If switches No. 1 and No. 2 are both closed, it will allow $1\frac{1}{2}$ amp. Switches No. 3, No. 4, etc., may control, 2, 2, 5, 10, 20, 30, etc., amp.

Thus any amount of current up to the full capacity of the box may be controlled in $\frac{1}{2}$ amp. steps.

Ordinary incandescent lamps are used widely for testing
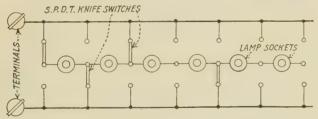
FIG. 221.—Very flexible load composed of lamps and S. P. D. T. switches.

loads, as they are very convenient to manipulate and replace. Instead of lamps, however, it is more desirable to use resistance units such as are shown in Fig. 220. Thus the advantages of flexibility and ease of replacement are retained, and as the units are not easily broken, they may be transported more readily than lamps.

A very flexible arrangement of lamp sockets and single-pole, double-throw switches may be easily constructed as shown in Fig. 221. This shows six units in screw sockets, all connected

in series. Between each unit and at the ends is connected a single-pole, double-throw knife-switch. Now if the first switch is placed up, the second down (as shown in Fig. 221), then the first unit is connected directly across the two terminals. If the third switch is placed up, then the third unit is placed in parallel. Then a switch may be left open, and say the fifth switch is placed down. Then units 3 and 4 are in series, but the two in series are in parallel with 1 and 2.

Thus it is evident that this arrangement permits of a variation from all in parallel to all in series, with any combination

Fig. 222.—Carbon rheostat.

of series-parallel. If 100-ohm, 100-watt units are used, the resistance of the arrangement may be varied from $16\frac{2}{3}$ ohms to 600 ohms, or in terms of current on a 100-v. circuit, from 6 amp. to 0.16 amp.

For heavy loads, a water rheostat is often used. This merely consists of two metal plates, placed in a pail or barrel of acidulated or salted water. The current strength is varied either by varying the distance between the plates or by varying the density of the solution. In this type the plate is lowered into the solution, thus presenting more and more active surface and increasing the resultant current accordingly.

Carbon Rheostat.—Another form of load, which is quite widely used, is the carbon compression rheostat. This utilizes the varying resistance produced between a metal and carbon

under varying pressure. A very useful carbon rheostat is shown plainly in Fig. 222.

Slide Resistor.—Oftentimes, due to a variable line voltage, the proper current cannot be obtained exactly. To overcome this, a very fine variable resistance is employed similar to Fig. 223. This is an insulated tube, wound with resistance wire, and arranged with a "slider" which may be moved back and forth, thus cutting in or out resistance in very small steps. This resistance may be connected in parallel with the load, but the general practice is to connect a slide of
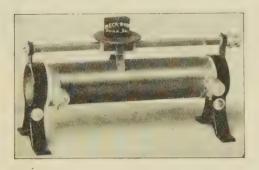
Fig. 223.—Ohmic slide resistor.

about 200 ohms in series with another resistance of 50 or 100 ohms, thus limiting the current to a total variation of about $1\frac{1}{2}$ amp. and obtaining larger variations on the main-load box.

Phantom Loads.—The voltage required to force current through the relay windings is very low, amounting to less than 5 v. in many cases. If current is drawn from a 110-v. circuit, by a series load, it is evident that only 5 v. is actually used, leaving 105 v. to be wasted in forcing current through the load. Instead, however, of using 5 amp. at 110 v. merely to obtain 5 amp. in the relay, we may transform from 110 to 5 v., and will get 5 amp. at 5 v. from the secondary, while the primary only supplied the same watts plus the primary losses at 110 v. The figure 5 was only assumed in the foregoing cases to illustrate the necessity of secondary voltage. In actual practice, the voltage is neither known nor desired to be known as it is varied until it produces the proper current which alone must

be measured, regardless of whether the voltage is 1 or 2 or 8 or 10 v. This is called a phantom load, as it permits of a large testing current and still draws only a small current from the testing supply. This will be given further consideration under testing connections. Typical phantom loads are shown in Fig. 224.
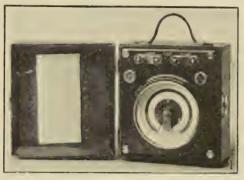
Fig. 224.—Typical phantom load boxes. (States Co.)

Standards.—The standard instrument for testing current relays is an ammeter. This should be a high-class instrument, having reliable accuracy, rugged in construction, dead-beat (*i.e.*, when current is applied, it should not overswing the mark, but indicate it quickly without oscillation or vibration). It should be correct on wide variations in frequency, and have large, open divisions making it easily read. The selection of an ammeter is a proposition demanding careful consideration from a great many points of view.

The induction principle is generally conceded to be the best for an all-around good instrument, and an exponent of the induction type is shown in Fig. 225. This embodies all the above enumerated points, and will give good service if handled correctly. This ammeter is arranged with two capacities. For instance, if the two links span the two outside posts, marked "10 amperes" as in the illustration, the pointer deflects to full scale on 10 amp., but if the links span the two posts marked "5 amperes" then full-scale deflection is obtained on 5 amp.

When the relays to be tested are all about the same capacity and are 120 amp. or less, it is possible to get an ammeter which reads full scale on the desired current. For instance, instead

of 5 and 10 amp., it might be 10 and 20; or 20 and 40; or 40 and 80; or 60 and 120.

Current Transformers.—Much greater flexibility is obtained by using a 5- and 10-amp. standard and a current transformer with variable ratio. The primary is connected in series with
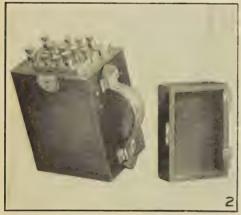
Fig. 225.—Westinghouse portable A.C. ammeter.
Fig. 226.—Westinghouse plug type transformer.
Fig. 227.—Westinghouse through type transformer.

the line and the current in the secondary is multiplied by the ratio of transformation to get the true current. A well-known transformer is shown in Fig. 226. This has primary values of 25, 50 and 100 amp., which are changed by rearranging the plugs according to directions which are furnished with the trans-

former. For higher current, the transformer in Fig. 227 is used. Two ranges may be supplied, 400 amp. and 1,600 amp. The primary is formed merely by passing the wire or cable through the hole. The ammeter is connected to the secondary terminals. By passing two turns through the hole, the ratio is changed from 400:5 to 200:5 or from 1,600:5 to 800:5 according to the transformer used. Four turns change the ratios to 100: 5 and 400:5 respectively. If the current is greater than 1,600 amp., the 10-amp. range on the meter is used, making it possible to measure up to 3,200 amp., using the same ratio or rather 3,220:10. There is a slight error when used in this manner.

The Trip Circuit.—The simplest way to test the trip circuit which operates from a separate source is to disconnect the leads from the breaker and substitute a lamp. If this is impracticable, the leads should be disconnected from the trip circuit of the relay, and the terminals connected to a source of supply in series with a lamp. If the relay is circuit-closing (shunt trip) the pilot or signal lamp will light when the relay trips. If the relay is of the circuit-opening type (series trip) the lamp is normally lighted, but goes out when the relay trips. When testing a shunt-trip relay, the contacts open the circuit when the relay resets, and may burn them slightly. Therefore, use a small lamp in testing, and before the last time the relay closes clean the contacts thoroughly with a piece of fine emery cloth or paper. Never use the red, crocus paper, as it often leaves a muddy coating on the contacts which prevents good electrical contact. It is good practice, after cleaning the contacts, to draw a piece of ordinary paper or cloth between the contacts in order to remove all traces of emery dust.

After cleaning, try the relay just once to make sure that nothing was damaged in cleaning.

Timing the Relay.—For ordinary relays, except those used for sectionalizing, a stop watch does very nicely for determining the time. First, the load is adjusted, at which the relay is to be timed; the relay is allowed to reset fully, and then the watch is snapped to start it and the load switch closed at the same instant. The instant the relay trips (lights the signal lamp), the watch is stopped and the time noted. The third snap resets the watch on zero, ready for the next trial.

For more accurate time, as is required for sectionalizing relays on a radial or ring system, it is necessary to use a cycle counter. This was described in a previous chapter.

THE ACTUAL TESTING

When all the apparatus, including load box, ammeter standard, trip lamp, and various leads and tools are ready, and before touching the relay, there are two things to be done, one of paramount importance and one a smaller detail. First, *short-circuit the current transformer* right at the secondary leads. A current transformer must never be open-circuited when there
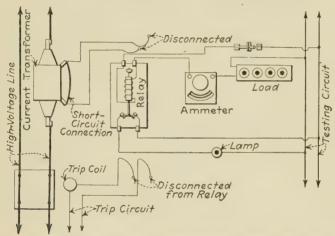
Fig. 228.—Testing a relay using a separate testing source and trip circuit.

is load in the primary as it not only may harm the transformer, but it may induce a voltage of several thousand volts, making it a source of great personal danger. No harm can come of short-circuiting a current or series transformer. Many modern installations have a permanently-mounted switch which short-circuits the secondary, but in its absence, a short lead with two heavy spring-testing clips should be used, and fastened so that they cannot possibly drop off. The second point is to wipe off all the dust or dirt from the cover before removing it.

Assuming, for the first example, that it is a 5-amp. bellows relay which is to be tested. It operates from a series transformer

placed in the high-tension line. A separate source is available for testing and a lamp load is used. The transformer is short-circuited; the relay disconnected at both top and bottom; the load, ammeter, relay coil and switch, all connected in series across the line; and the trip connected in with a signal lamp, as in Fig. 228.

Of course, if the circuit may be interrupted, it is not necessary to disconnect the trip; the breaker itself actually may be opened when the relay trips. This is really preferable, but often impossible to do. The switch is closed, the load adjusted until the meter shows the correct current passing; then the switch is opened and the relay fully reset. Quickly closing the switch, snap the stop watch to start in, and the instant the lamp lights (or the breaker trips), snap the watch to stop it. This gives the time of delay between overload and tripping.

The Cycle Counter.—To obtain very accurate time, as is necessary with sectionalizing relays, a cycle counter is connected in, to automatically time the delay. The self-winding clock is permanently connected across the source of supply. The escapement magnet is connected in series with a resistor, and is energized as soon as the switch is closed. Then it starts counting the cycles, until the relay contacts close, thereby short-circuiting the escapement magnets and stopping the counter instantly. The cycle counter then indicates the number of cycles which have elapsed between the instant of load and closing of contacts.

Dividing this number by 60 gives the number of seconds on a 60-cycle circuit, and dividing by 25 gives the seconds on a 25-cycle circuit.

If a circuit-opening relay is used, the escapement magnet is placed in series with the contacts with one switch controlling both load and trip. Then the counter starts when the switch is closed and stops when the switch is opened.

Some engineers prefer to leave the circuit intact and connect in the testing load as shown in Fig. 229. This scheme is excellent provided the primary of the current transformer is not energized, and there is no possibility of its being short-circuited. In this case, the natural impedance of the transformer secondary prevents any appreciable current being diverted from the

relays. It will be noted that other instruments in this circuit will also receive the test current. This method will detect any short-circuit in the transformer or wiring, but a separate continuity test may be made by opening the circuit and inserting potential to see that no open circuits have developed. This test may be made on a few amperes D.C., but if A.C. is alone available, it must be remembered that full current cannot be forced through the transformer secondary unless the primary or secondary is short-circuited.
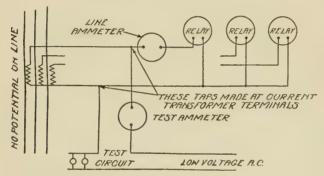
Fig. 229.—Testing a relay without disconnecting from the circuit.

Testing Heavy-current Relays.—The problem of testing a heavy-current relay is more difficult of solution, as it is necessary to interrupt the circuit in most cases, unless the load can be built up on the lines. In this case, however, it is very difficult to get an accurate time as it is hard to apply a heavy load in a quick, accurate manner.

A good way to test series relays up to several hundred amperes is to use a phantom load, obtained by using an old series transformer inverted. The connections are shown in Fig. 230. The relay is disconnected from the main line. (This is not necessary if it is a low-tension circuit and if it has no current flowing.) A short section of heavy cable is run through two transformers A and B and connected to the relay coil F. Current is now fed into the secondary of transformer A with load D and switch E in series. This current induces a voltage in the loop of wire, and since its resistance is low, a heavy current

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flows in the relay circuit. This is measured accurately by the transformer *B* and the meter *C*.

For instance, using transformers 400 to 5 amp., when meter *C* reads 5 amp., it will be known that there is 400 amp. in the relay circuit. It may, however, take about 6 amp. from the line to produce this current. Should one turn in transformer *A* not give enough current, the turns may be increased to
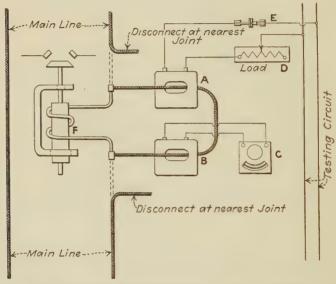
FIG. 230.—Using an inverted series transformer to supply a heavy "phantom" current.

two or three and the current from the load increased accordingly. A good combination for 400 amp. is to use a 1,600-to-5 transformer at *A* with four turns of heavy wire for the primary.

The trip circuit may be connected with a lamp or cycle counter as previously described.

Making the Adjustment.—There are so many different makes of relays and principles of operation that it is impossible to give explicit directions for the adjustment of each and every one. This, however, is hardly necessary, as each manufacturer gives directions for readjusting his particular relay and, of course, these should be followed. There are, in general, two separate

objects to be obtained by adjustment—starting current and time delay on a definite current.

In the plunger-type relays, the starting current is adjusted by varying the position of the core on the stem. This stem is generally threaded, and the core or plunger screwed into position and locked with a setscrew or locknut. When adjusting, loosen this set, then raise the plunger (screw it up) to lower the starting current or lower it to raise the amount of starting current. When the correct position is found, lock the plunger firmly in position so that the excessive vibration found in this type of relay cannot jar it loose. If there are springs which tend to offset the weight of the plunger, these may also be called into play to change the starting current.

In the induction type, the adjustment is generally done by pulling out, or letting in, some of the spiral spring which resists the turning effort of the disk. This is a delicate job and should only be undertaken by an experienced instrument man. Slight adjustment can sometimes be made by changing the position of the torque compensator with respect to the base. This changes the amount of leakage flux as the base diverts more or less of it, but this changes the shape of the curve more than the starting current.

The time of the bellows and oil-lagged relays is varied both by the distance of contact travel and the size of the opening in the needle valve. The contact disk is generally placed loosely between two nuts on the threaded shaft and may be raised or lowered, thereby making the plunger travel a longer or shorter distance and giving a longer or shorter time delay. To obtain larger variations, it is necessary to grind a flat place on the valve, to allow greater escape of air or oil on long-time settings. Care must be taken, however, that the valve is not ground too much. It is preferable not to touch the valve, but to make a curve or set of readings, and set the relay time according to this curve.

The time of induction-type relays is varied by moving the permanent magnets in or out.

Moving the magnet in toward the center of the disk gives a shorter time and moving it out (to within $\frac{1}{8}$ in. of the edge) gives a longer time. Great care must be taken that the disk

does not touch the magnet as it turns, and that there is no iron dust or filings on the magnets which may in time rub on the disk. A feather or a piece of soft-iron wire, (such as an unbent paper clip), are excellent in removing filings.

Before leaving a relay, make sure that every accessible screw and nut is tight; see that the contacts are clean; no loose connections; no burnt coils or insulation; no dirt or dust; and that all moving parts move freely without sticking or rubbing. Also see that the leather on bellows relays is soft and pliable, using, if necessary, a little neatsfoot oil to keep it soft. Make sure that all connections are returned exactly as found. If there are several connections to be removed and there is any possibility of getting them twisted, make a sketch of the relays and terminals, and number each terminal, 1, 2, 3, etc., on the sketch. Then as the wires are removed, tie a small tag on each one, marked 1, 2, 3, etc., so there will be absolutely no danger but that the leads are correctly replaced. Then after all connections are completed, remove the short on the series transformer. Connect an ammeter in parallel with the current coil and see by its indication that current is flowing. The ammeter will divert part of the current from the relay. Connect a voltmeter across the trip-circuit terminals and see by its indication that the trip circuit is intact right up to the relay contacts.

Plotting the Results.—The time results under various loads are easily plotted in curve form or tabulated, thus rendering a permanent record of the action of the relay under various conditions and forming a ready source of reference by which the time of the relay may be easily changed in definite manner, as might be necessary due to a change in the distribution of the load or the addition of various equipment.

If the results are tabulated, they should be somewhat similar to the table shown in Fig. 231. The vertical columns are the results of the various lever settings and the horizontal lines are the various loads. Proceed with the test as follows: Set the relay to No. 1 setting and adjust the load to one and one-half times the tap setting. Thus if the 5-amp. tap is used, the current must be 7.5 amp. The column may be in actual current or in "per cent load." Apply the load and note the time. It is 0.5 sec. (30 cycles on the cycle counter on 60-cycle circuit).

Put this down at the intersection of the No. 1 setting column and the "one and one-half times current setting" line. Try No. 2 setting. The time is now 1.1 sec. Try No. 3 setting. It is now 1.7 sec. And so on until all the settings have been tried, the load remaining at one and one-half times or 7.5 amp. during these 10 tests.

Now change the load to two times the current tap setting and take 10 more readings with the different lever settings. This gives the figures for the second horizontal line.

Relay Service:	Location:			Date:
Voltage ⟶	*118 Per Cent. Normal*			*59 Per Cent. Normal*
Millivolts Setting ⟶ 2	5	10		5
Applied Millivolts	*Tripping Time in Seconds*			
2	8.0			
5	1.4	8.0		
10	0.7	2.0	8.0	2.2
15	0.5	1.3	2.8	1.0
20	0.4	0.8	1.6	0.6

	Time in Seconds to Trip									
1.5	0.5	1.1	1.7	2.3	2.9	3.7	4.7	5.9	7.2	8.6
2	0.4	0.8	1.1	1.5	2.0	2.5	3.1	3.9	4.6	5.6
Times 3	0.3	0.6	0.8	1.1	1.4	1.8	2.2	2.7	3.2	4.0
Current 5 Tap	0.3	0.5	0.7	0.9	1.1	1.4	1.7	2.0	2.5	3.0
Setting 10	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.7	2.0	2.4
20	0.2	0.4	0.5	0.7	0.8	1.0	1.2	1.5	1.8	2.2
30	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.4	1.7	2.0
50	0.2	0.3	0.4	0.6	0.7	0.8	1.0	1.3	1.6	1.9
Lever Setting	1	2	3	4	5	6	7	8	9	10
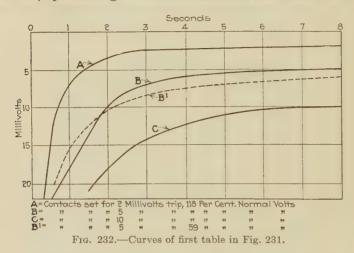
Fig. 231.—Tables of relay accuracies.

When getting heavier loads, say above 20 times or above 100 amp., especially on the high-lever settings, be sure the winding is thoroughly cooled off before making the next test as sometimes a repeated heavy overload will change the time due to the self-heating.

If preferred, a curve may be plotted on cross-section paper as shown in Fig. 232. The point of intersection between the current and lever setting is found and a dot marked. When a number of points have been located, a smooth curve is drawn through the points. A table like Fig. 231 is generally made

first and then the curves plotted. Intermediate time is easier to locate on a curve than on a table.

Another important feature on a large system is the keeping of a card system giving complete data on each relay together with its actual time and load setting. The layout of the system will give the identifying number on each relay on each circuit and then, by referring to this number in the card index, the per-

A= Contacts set for 2 Millivolts trip, 118 Per Cent. Normal Volts
B=   ”   ”   ” 5   ”   ”   ”   ”   ”   ”   ”
C=   ”   ”   ” 10   ”   ”   ”   ”   ”   ”   ”
B¹=   ”   ”   ” 5   ”   ”   59 ”   ”   ”   ”

Fig. 232.—Curves of first table in Fig. 231.

formance of this relay under certain combinations of load conditions can be accurately forecast. This also forms an accurate method of retiming a system in case of revisions or additions to the load.

TESTING VOLTAGE RELAYS

The apparatus generally used for testing voltage relays, both under and over, is a small portable transformer, a means of varying it, and a reliable standard. Of course, if a high enough source is available, it is unnecessary to have a small step-up transformer, but only means of cutting the voltage down to the proper amount. A small portable transformer is shown in Fig. 233. While designed to step down from 400 or 200 to 100 v., with accurately compensated ratio, it may also be used to step up from 100 to 200 or 400 v. with good results. The potential is varied by means of the adjustable slide. This slide is con-

nected directly across the line, while the potential is taken between one line and the slide, thereby insuring a close graduation from zero to maximum voltage.

One form of a reliable standard voltmeter is of the moving coil, dynamometer type, which is without question the best principle of operation to use for an accurate, reliable, rugged test instrument. Voltmeters come with two or more ranges, *i.e.*, they indicate full scale on 150 v., or by changing to another

Fɪɢ. 233.—Westinghouse portable voltage transformer.

terminal, they indicate full scale on 300 v.; or on 300 and 600. A good combination is a 75- and 150-v. voltmeter, with an external multiplier, making full scale 300 v. and 600 or 750 v.

In approaching an installation, the first thing to do is to disconnect the trip circuit and then open-circuit the potential transformer. Never short-circuit it, (as in the case of a series transformer), as it will invariably blow a primary fuse or burn up the transformer. Then clean the dust and dirt from the cover before opening it.

Connect the apparatus as in Fig. 234. Inspect the relay mechanically, tightening all screws and nuts; clean the contacts

and see that all moving parts are free to turn without rubbing or friction; see that the springs are intact, no burnt coils, and no filings clinging to the magnet.

Then close the test switch and see that the contacts close
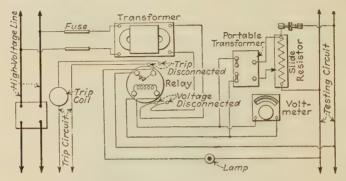
Fig. 234.—Testing a voltage relay from a separate source.

positively at the right voltage. If desirable, a table or curve may be made showing the relation between lever settings and closing or opening volts. Or a curve may be made showing the length of time required to close the contacts. Another set of test connections are shown in Fig. 235.
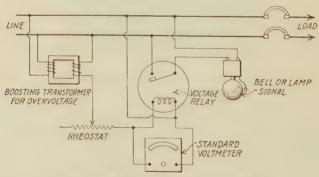
Fig. 235.—Connections for testing a voltage relay.

Power-directional Relays.—Tests on a reverse power relay generally comprise a complete test on the overload element the same as described previously, and a thorough mechanical inspection is given to see that all parts are free to move without

friction. In spite of all calculations of overload currents, distorted phase angles and other effects, there is only one sure way of determining if a certain installation of relays will protect, and that is by actually overloading or short-circuiting the lines, or in intentionally producing the disturbance which it is desired to have cleared in case of its accidental occurrence. These are really installation tests and, once made, need not be repeated, unless conditions occur which necessitate a revision of lines or apparatus. If it be known that the relays and connections give protection (from actual test) then it only becomes necessary to know that the instruments are mechanically intact and this is determined by periodic inspection.

In testing the directional element, both voltage and current should be supplied to see that the relay functions correctly on reversal of current. In many cases it is desirable to step the voltage down to 1 or 2 per cent of normal and put on a heavy overload at low power factor and see if operation is satisfactory.

Reverse-phase Relays.—Reverse-phase relays are tested in the same manner as voltage relays, except that two circuits are used. After the usual mechanical inspection, one phase is disconnected and the relay should trip; or if the voltage drops to a certain value it should trip; or if either phase is reversed, the relay should trip.

Temperature Relays.—Wherever possible, the temperature relays should be tested by packing a thermometer in or near the exploring coil and noting if the indications correspond to the relay action. On some types, it is possible to remove the exploring coil as a unit. In this case, the exploring coil may be placed in a heated chamber, together with an accurate thermometer and the relay and thermometer compared from time to time as the temperature changes.

CONCLUSION

While directions have been given for the selection, installation and care of various relays, it must be understood that what applies to perfection in one case may fail in another. Consequently, for any given installation, it is necessary to study the system, the location of apparatus, their behavior

under varying conditions, and finally to devise a system of protection which will cover the great majority of points, for it is frankly acknowledged that every point cannot be covered by any relay or combination in every case.

The subject of relays and their protection of circuits and apparatus is an engineering profession by itself and is capable of great possibilities in improvement.

However, even with the present relays and systems, they are so little understood that the economies and improved service resulting from the use of relays have not been taken advantage of by operators as fully as they should be. Then, too, many operators have not yet realized these advantages. Others that have used relays to a limited extent have in no way exhausted their possibilities.

The electrical engineers of the country are still at work on the subject of protection and uninterrupted service, and are gradually and thoroughly investigating each and every possible protection problem and each year sees many old problems successfully solved. So it is to be hoped that soon such things as burnouts and short-circuits interrupting service will be matters of the past.

LOCATING FAULTS IN FEEDERS AND WIRING

Although protective relays may sectionalize and isolate defective feeders and apparatus with more than human speed and accuracy, yet it is often a difficult matter to locate the actual fault. In the factory the fault may be in a conduit or duct; in an underground distribution system, it may be in a subway between manholes; or in a long-distance transmission system, the location of the fault may require miles of line patrolling to actually see where and what the trouble may be. It often happens that relays may isolate a line and then considerable time is spent in trying to locate the fault, where in other cases it may be that the fault clears immediately upon isolation.

The following chapter while not a complete exposition on the details of fault location, especially as applied to high-tension lines, will nevertheless give the basic principles of the methods used in finding the exact location of the fault.

The most commonly met defects or faults in the wiring of any system are: (1) open-circuits, or breaks, caused by a broken wire or blown fuse; (2) short-circuits, or crosses, caused by two metal conductors of different potentials touching each other; and (3) grounds, caused by a live metal conductor touching a metal conduit or other foreign metal. An open-circuit is in reality a complete break, or condition of infinite resistance in a supposedly continuous conductor, but there are conditions when the fault may have any resistance from a few ohms to many thousand. In such cases, however, the fault is usually accompanied by a ground, as for instance, if a feeder in a metal conduit should become open-circuit, the voltage might cause the two ends to weld fast to the conduit, thus introducing only a slight resistance in the line producing a ground.

A short-circuit may be either a low-resistance or "dead" short, or a high-resistance short-circuit, commonly called a

leak. A "dead" short will usually manifest itself in a violent manner by blowing a fuse or breaker, and the fuse cannot be replaced or the breaker reset until the fault is located and cleared. A high-resistance short may not draw enough current to blow a fuse, but it constitutes a waste of current, and if the leak be confined to a small space, the resulting heat may start a fire. As before, short-circuits are often accompanied by open circuits and grounds, due to the violence of the short-circuit either burning the wire in two or welding it to the metal conduit.

On low-potential circuits, a single ground cannot cause any damage; but should a second ground occur on a wire of opposite polarity, the two grounds will cause a short-circuit, its violence depending on whether the grounds are of high resistance or low resistance. There are a great many cases where it is advisable to ground a machine frame or wire in order to limit the potential between any part of the circuit and the ground; for instance, the secondary of a 110-v. lighting circuit is usually grounded so that there can never be a dangerous potential between the wiring and ground in case the transformer should short-circuit between primary and secondary. Another case is where the neutral of a three-wire system is grounded so that the potential between either outside wire and the ground can never be greater than the potential between either outside wire and the neutral. In testing for faults it must be remembered that all grounds are not accidental; some are intentional and must be taken into account in the test.

Apparatus Required.—Perhaps the most commonly used testing apparatus is a magneto and polarized bell, such as are often found in the old-style telephones. This is shown in Fig. 236. The magneto and bell are mounted in a compact portable carrying case, connected in series and supplied with a long pair of leads. This outfit is used extensively to test wiring for opens, shorts and grounds as will be described later. A special fuse-testing panel is shown in Fig. 237.

On long lines, however, the magneto and bell test for open circuits, or rather for continuity, must be used with great caution and intelligence as often there will be enough capacity or condenser effect to allow the bell to ring even though there be an open circuit.

The testing apparatus shown in Fig. 238 is best in a case like this. This consists of an electric vibrating bell, or a lamp, mounted in a case with a number of dry cells, and forms a convenient test box, but is not so efficient as the magneto, as
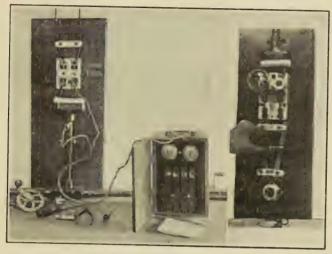
FIG. 236.—Magneto and bell test.   FIG. 237.—Simple fuse-testing panel.
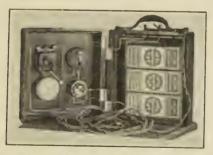
FIG. 238.—Testing set consisting of several dry cells mounted in a portable case with a bell and small lamp.

the voltage is low and the test current comparatively high. It will not show up many high-resistance grounds which might be detected by the magneto. The magneto develops a comparatively high voltage and takes very little bell-operating current.

If low-potential alternating current is available, a small potential transformer, properly equipped with protective lamps and test leads, forms an excellent piece of apparatus for testing for grounds, opens, and shorts. In this, the primary is connected in series with a fuse to a 110-v. A.C. circuit. The secondary should have taps connected to a dial switch so that any voltage from 100 to 2,000 may be obtained in 100-v. steps.

A galvanometer or a low-reading voltmeter may be used in series with a few dry cells for the same purpose. This has the advantage that the resistance of the ground, open or short may be roughly calculated from its indication.

Testing for Opens, Shorts or Grounds.—Let us assume a factory running a number of motors and lighting circuits; say one department reports that a certain motor will not run. The repairman takes his voltmeter and magneto set, and going to the department where the motor stopped should first conduct an investigation among the ones who operate the motor, and diagnose the case much in the same way as a physician diagnoses human ills. Was there any unusually heavy load applied when the motor stopped? Did the motor heat up excessively? Did someone throw the starting compensator handle from starting to running position too quickly?

If the trouble is merely a blown fuse, the cause of blowing should be determined to avoid recurrence. If no one can report any difficulty, remove the fuses and test the voltage on the line side of the fuse. Then test the fuses separately with the magneto, or with a special fuse-testing panel, such as shown in Fig. 237. To do this, connect the two fuse terminals to the magneto outfit, and turn the handle. If the bell rings, the fuse is intact, but if it does not ring, then it is blown out. On a two-wire circuit, the voltage may be tested on the load side without removing the fuses, where a lack of voltage will indicate a blown fuse. But this cannot be done on a three-wire or a polyphase circuit unless it be definitely ascertained that there is no connected load, as the current from another phase may feed backward through the load and operate the voltmeter, thus giving an indication of good fuses. It takes at least two blown fuses to kill the secondary voltage of a polyphase circuit with a con-

nected load. Figure 239 shows the proper method to pursue
in locating a blown fuse.

As we are dealing with feeder and wiring faults, assume that
the fuses are good but there is no voltage; or on a polyphase
circuit, that there is no voltage on at least one phase. Proceed
to the next fuse junction nearest to the source and perform
the same test. Perhaps a blown fuse will be found here that
kills the voltage at the motor-fuse block. Assume for the first
case that a blown fuse is found and upon replacement it blows
out immediately. Since the other end of the line is open-
circuited, it shows that there is a short or a ground in this
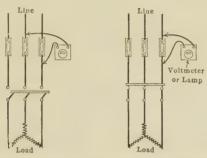
Fig. 239.—At left, when load is disconnected, fuses are tested by connecting
voltmeter between the line side of one fuse and the load side of another. At
right, testing around the fuse.

line. *Now remove all fuses or connections on both ends of the
line.* If the line is in metal conduit, connect one magneto
lead to the metal conduit, or if it is open wiring, connect the
lead to the nearest water pipe. Connect the other magneto lead
to one of the wires in the isolated section. Turn the magneto
briskly, and if the bell rings, the wire is grounded; no ring
indicates an ungrounded line. Try the other lines in succession.
Assume for the present that all lines in the section under test
are free from grounds.

Now connect the two magneto leads one to each of two wires
in the section under test and turn the handle. A ringing bell
indicates a short-circuit between two wires, which in this case
would be the cause of the blown fuses.

It is very seldom that a feeder or heavy wire will open-circuit,
but the test is made by grounding the far ends of the wires in the

section under test and then testing with the magneto between each at the opposite end. A ring will indicate a continuous circuit, while no ring will indicate an open circuit.

Open circuits frequently occur in lamp cord and light wiring by the wire breaking inside the insulation, while on the outside it appears to be intact. These cases, however, are not difficult to find as they generally occur in single units such as lamps and small motors, and seldom on distributing feeders which carry a heavy load.

Accurately Locating the Short-circuit.—After localizing the fault to a section between two fuse centers, the fault often may be accurately located by a careful inspection, especially in open wiring, but if it is in conduit, and quite a long run in the section under test, some method is necessary to determine the approximate location so that only the wires affected in smaller section between two outlets need be pulled out.

A short-circuit may be most easily localized by a direct-current reversing commutator and a compass. Or a simple reversing switch operated by an assistant has the same result. First make sure that the line is dead at both ends; then connect a 6-v. storage battery, through an adjustable resistor, ammeter and double-pole double-throw reversing switch, to the faulty line. Adjust the resistance so that 5 or 10 amp. flows through the short. The assistant is instructed to reverse the switch about every 10 sec. The cover is removed from the nearest junction box, and the compass held against the wire. If the fault is past this box, the compass will reverse every time the assistant reverses his switch. If the compass reverses, proceed to the next box and see if the compass works. If so it shows the fault to be further on, so a test is made at the next box, and so on until a junction box is reached where the compass does not deflect.

A similar method that may be used where alternating current is available is formed by passing 5 or 10 amp. through the faulty cable and the short-circuit. Instead of the compass, a small piece of transformer iron, about 1 in. wide and several inches long, is bent in a semicircle and about 10 turns of No. 18 or 20 B. & S. gage insulated magnet wire wound around the center. Flexible leads are used to connect this winding to a

telephone receiver. Figure 240 gives an illustration showing the use of both methods.

The junction box nearest the application of current is opened and the soft iron held over the wire. A buzz indicates that the fault is further on; so each outlet is tested in turn until one is reached where no buzz is heard, thus indicating that the fault lies between this outlet and the one last tested. The remedy lies in pulling out the faulty cable, or calculating the exact location of the fault and cutting the conduit at the fault so that an outlet and splice may be made without interfering with the rest
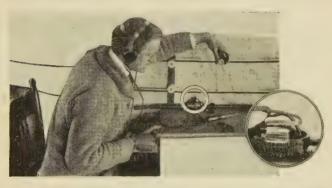
Fig. 240.—Two methods of locating short-circuits in a cable. With direct current a compass is used, with alternating current the tester uses telephone receivers and the detector coil shown encircled.

of the cable. While this method is described only for small systems, yet it is to be understood that the same principles only on a larger scale may be applied to long-distance transmission lines.

Localizing a Ground.—The methods used in locating a ground are very similar to those used for shorts. Instead of passing the current through the two wires and the short, the source is connected between the grounded wire and any convenient ground, the resulting current passing through the accidental ground on the wire. Either direct current and compass may be used, or alternating current and telephone receiver.

This method is very effective with radial systems as it is only necessary to test each pair of feeders at the branches and

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follow out the wires that indicate grounds or shorts until the fault is found.

Calculating the Location of Short or Ground.—If the short or ground is on a single line which may be isolated by disconnecting at both ends, and if the resistance is accurately known, then the location of a fault may be quite accurately found by a measurement of the resistance either by a Wheatstone's bridge or by the voltammeter method.

For instance, assume two wires 500 ft. long and each wire measuring 0.05 ohm.

Passing 10 amp. (adjusted by rheostat and measured by an accurate ammeter) through the short, assume the potential drop across the cable to be 0.8 v. or 800 m.v. The resistance of the two sections of wire as far as the short, plus the resistance of the short, is 0.08 ohm. Now connect the two far ends of the cable tightly together, and measure again. Assume the voltmeter now shows 0.733 v. or 773 m.v., thus indicating that paralleling the resistance of the short with the remaining section of good cable reduces the resistance from 0.08 to 0.0733 ohm. Consequently the resistance of the good cable, *as far as the short*, may be calculated from the formula:

$$X = C - \sqrt{(b\text{-}c)(a\text{-}c)}$$

in which X = the total resistance of cable to short.

a = the total known resistance of good wires.

b = resistance measured with ends open.

c = resistance measured with ends closed.

Or in our example:

$$X = 0.0733 - \sqrt{(0.08 - 0.0733)(0.1 - 0.0733)}$$

which equals 0.06 ohm.

This is the resistance of two wires to the short, so each wire will be 0.03 ohm. If the resistance of 500 ft. is 0.05 ohm, then 0.03 ohm will represent 300 ft., showing that the short is 300 ft. from the beginning of the cable.

A ground may be located in the same manner, if the resistance of the cable be known, by measuring the resistance between cable and ground with the far end of cable insulated and then measuring the resistance with the far end grounded, although in this

case accuracy is not high unless the line be comparatively long and high resistance and the ground resistance practically zero.

Two-ammeter Method.—Another way of approximately locating a ground in a heavy feeder is by the two-ammeter method, connecting an ammeter in each leg of the circuit and noting the division of the current. To do this first clear both ends of the line and then join the two far ends together tightly. Then connect a 5-amp. D.C. ammeter in series with each wire, connecting the opposite side of the ammeters together; from this joint connect a storage battery and resistor to the ground. The connections are shown in diagram in Fig. 241.
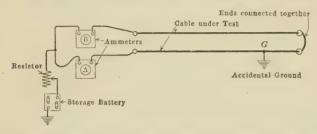
Fig. 241.—Locating ground on a heavy feeder by measuring the division of current by ammeters A and B.

The current through meter A needs to go only through part of one feeder to reach the break, but the current through meter B must not only traverse the total length of one cable, but also the remaining section of the grounded cable. Since the currents divide inversely proportional to the resistance of the cable they must travel and since this resistance is proportional to the length, it follows that the ratio of the two meters is inversely proportional to the two lengths of cable. Or the ratio of one reading to the sum of the two readings is the same as the ratio of the opposite section to the break is to the total length.

For instance, if meter A reads 3 amp. and meter B reads 2 amp. and since this division is inversely proportional to the resistances, the proportion is $3 : 2 = AG : BG$. Or call the whole circuit 100 per cent, then $3 : 2 = (100\text{-}AG) : AG$ or $2 : 5 = X : 100$. Solving this for BG or X gives 40, which means that the fault is 40 per cent of the total length of the cable away from the meters.

For very accurate results with the two-ammeter method, it is necessary to figure the resistance of the ammeters and connecting cables as so many feet of equivalent cable. For instance, if the cable being tested is 500 ft. long (1,000 ft. for two conductors) and has a resistance of 0.05 ohm per 500 ft., and if the resistance of the meter and connections from the dividing point to the cable is found to be 0.002 ohm, then it is evident that the meter and connections have a resistance equivalent to 20 ft. of cable. To measure the resistance of the meters, pass about 5 amp. through the meter on all connections, and then with a millivoltmeter take the drop from the dividing point between the meters to the nearest point on the cable, including all connections and joints. Say this is 100 m.v. Then the resistance is $R = \dfrac{E}{I}$ or 0.1 v. ÷ 5 amp. = 0.002 ohm. Since the cable is 0.05×500 ft. or 0.0001 ohm per ft., it follows that it takes 20 ft. to make up a resistance of 0.002 ohm. If the other meter measures the same, then in making the final calculation, it is necessary to figure the total length of cable as (500 + 500 + 20 + 20) or 1,040 ft. instead of merely 1,000 ft. So in our previous example the fault would figure 40 per cent of 1,040 or 416 ft. away from the end being tested. But we already know that the meter is equivalent to 20 ft., so we must subtract this, making the actual location of the fault 416 − 20 or 396 ft. away.

The Fault Localizer.—A much safer method to locate a ground in a heavy cable or feeder is by the Westinghouse fault localizer. This instrument, a diagram of which is shown in Fig. 242, has three terminals two of which are connected to the respective wires in a two-wire feeder and the other through a source of D.C. potential, ammeter and lamp bank to the ground. The central knob is then turned until the galvanometer shows no deflection upon pressure of the key. The point on the scale that now lies directly below the O mark indicates directly the percentage of cable length to the ground. One post is marked "red" and one "black," so if the reading appears in red on the scale, then the ground is on the line connected to the "red" post. For example if the scale showed 60 per cent in black, then it would be known that the line connected to the black

post was grounded, and if the total length of line was 100 ft., then the ground would be 60 ft. (60 per cent of 100) from the instrument.

In principle of operation, the fault localizer is somewhat similar to a specially constructed Wheatstone bridge. As will be seen in the diagram, Fig. 242, there is a heavy shunt with three terminals which carries the main current, thus allowing a comparatively small slide wire to be used. The slide wire is wound on a circular spool in two sections, and on each section
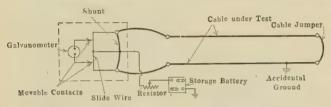
Fɪɢ. 242.—Diagram of connections of Westinghouse fault localizer.

is a movable contact. It will be readily seen that the current between the center post and the fault divides through the two sides of the shunt inversely proportional to the resistance of the loop from the instrument to the fault. The currents in the slide wires being proportional to the current in the shunts, it follows that by moving the contacts so they span more of one and less of the other wire, there will be a point reached where a balance is reached. This point indicated on the movable scale gives the location of the fault in percentage of the total loop.

L. & N. Power Bridge.—When an attempt is made to localize a fault in a very heavy and comparatively short cable, it will be found that the utmost care must be taken to avoid contact resistance in the joints between the instrument and the cable. Even the slight resistance of the connecting leads may introduce a serious error. For instance, if the contact resistance is 0.001 ohm and the wires were of such a size that 0.001 ohm were equal to the resistance of 20 ft. of the cable, then it means that there would be an error of 20 ft. in the location of the fault. This clearly demonstrates that the necessity of making as perfect a contact as possible between the instrument and cable cannot be too strongly emphasized.

To partly overcome this difficulty, the Leeds & Northrup power bridge has heavy leads permanently connected to the bridge and heavy clamps on the ends for securely clamping to the cable. This is shown in Fig. 243.

In principle of operation, this bridge consists of a slide-wire bridge with a very sensitive galvanometer mounted in the carrying case. The low resistance slide wire is mounted on a circular
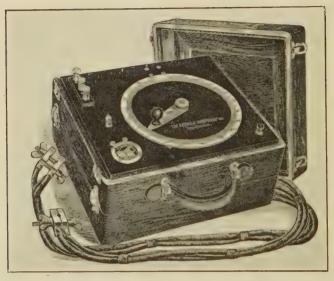
Fig. 243.—Leeds & Northrup power bridge.

block inside the case and arranged with a very positive movable contact. This contact is rigidly attached to a shaft which carries a knob and pointer moving over a calibrated scale. The wire is made large enough to carry about 5 amp., thus giving a readable deflection for a short movement of the contact. If the occasion demands, this current may be increased to 8 amp. to obtain very accurate results, but this heavy current should not be left on longer than is absolutely necessary.

The scale is divided into 1,000 divisions, but the leads are arranged to equal 10 divisions of the slide wire, so the pointer will only go from 10 to 990 on the scale. It will thus be seen that

the slide wire actually begins at the ends of the cable, thus entirely eliminating lead resistance.

In using the instrument to locate grounds, the line is first cleared at both ends and then one end of the cable is tightly clamped together. Care must be taken to avoid contact resistance here.

The battery is connected to posts marked *Ba*. The post marked *Gr* must be securely grounded. Sufficient battery must be used to obtain a readable deflection from a slight change, or resistance must be inserted if the current is too large. The connections are shown in Fig. 244.
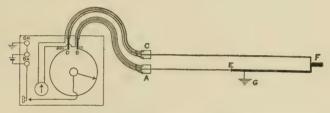
Fig. 244.—Diagram of connections of L. & N. power bridge.

The bridge locates the fault by the Murray loop method. If, for instance, the bridge is balanced so that the galvanometer shows no deflection when the pointer is at 300 and the key is pressed, then it means that the distance from block *A* to the fault is $\frac{300}{1,000}$ of the total distance.

LOCATION OF FAULTS WHEN THE LOOP IS COMPOSED OF DIFFERENT CROSS-SECTION CABLES

When there are cables of varying cross-section in the loop being tested, the fault is usually located by reducing the cables to equivalent lengths of one size cable.

For instance, in diagram, Fig. 244, assume that there are three sections of cable of various sizes and that these sections are as follows: Length *A* to *E* is composed of 550 yd. of 25,000 cir. mils, length *EF* is 500 yd. of 40,000 cir. mils, and length *FC* is 1,050 yd. of 30,000 cir. mils. These lengths must be reduced by calculation to equivalent lengths of one size, and for this purpose it is best to select the largest size. Since the

resistance is inversely proportional to the cross-section and directly proportional to the length, it follows that the calculation is merely an inverse proportion. To reduce the first length, the equation becomes:

$$550 : 25,000 = x : 40,000$$

which gives x as 880 yd., meaning that 880 yd. of 40,000-cir. mil cable is equal in resistance to 550 yd. of 25,000-cir. mil cable. Reducing the rest in a similar manner gives the following:

550 yd. of 25,000 cir. mils = 880 yd. of 40,000 cir. mils.
500 yd. of 40,000 cir. mils = 500 yd. of 40,000 cir. mils.
1,050 yd. of 30,000 cir. mils = 1,400 yd. of 40,000 cir. mils.

This makes the total resistance of the loop equivalent to 2,780 yd. of 40,000. Now if the bridge balances at a reading of 372.5 this indicates that the fault is 37.25 per cent of the total distance or 1,035.5 equivalent yards from E. Of this, 880 are in the stretch AE, leaving only 1,035.5 − 880 or 155.5 yd., which is the distance from E to the fault.

Burning Out the Fault.—When the fault, either cross, ground or partial open, is of a high resistance and it is impossible to locate it by ordinary methods, it is sometimes permissible to burn it out. This, however, must be attempted only with the greatest precautions such as having pails of sand or reliable fire extinguishers ready for immediate use should the burning-out process start a fire.

To do this, connect a high potential so that it feeds current through the fault and then increase the current until something happens. This something may be a fire, a melted conduit, a ruined section of wire, additional trouble communicated to other sections of wire, or merely a carbonizing of the fault. If the fault becomes carbonized sufficiently to pass about 5 amp. through from a low-voltage battery, then it is easy to locate the fault by the previously described methods.

In any case burning out a fault is a method which must be resorted to only in an extreme case as practically all faults may be located in a much safer and gentler manner by a little clear thinking and sound reasoning.

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